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COMPUTER PROGRAMS FOR EMC BASED ON THE METHODS OF MOMENTS.(U)
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COMPUTER PROGRAMS FOR EMC BASED ON THE METHODS OF MOMENTS

Syracuse University

Bradley Strait

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APPROVED: Jacob Scherer

JACOB SCHERER
Project Engineer

APPROVED: David C. Luke

DAVID C. LUKE, Lt Colonel, USAF
Chief, Reliability and Compatibility Division

FOR THE COMMANDER: John P. Huss

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This report describes several user-oriented computer programs based on the method of moments that are available and can be useful in solving problems of electromagnetics and electromagnetic compatibility. Emphasis is placed on applications, relative availability, and limitations of the programs rather than on mathematical details or programming descriptions. Attention is limited to moment-method based computer codes suitable for ~~a~~ treatment in the frequency domain and also in the next page

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time domain of problems involving the electromagnetic behavior of thin wires and rods, ~~b)~~ treatment in the frequency domain of problems involving radiation or scattering by two-and three-dimensional conducting and/or penetrable bodies, and ~~c)~~ frequency domain coupling of electromagnetic energy through apertures in conducting bodies.

ACKNOWLEDGEMENTS

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It is also a pleasure to acknowledge the work of the Electromagnetics and System Research Group at the Lawrence Livermore Laboratory, Livermore California. Many publications of that group are referenced here. Much of their work is directly related to the objectives of this report (for example, see [177]).

CONTENTS

1. INTRODUCTION

The Method of Moments is an analysis technique that has been applied successfully to various problems of electromagnetics. In particular the method is useful for treating certain problems in the general area of electromagnetic compatibility and for providing relatively general and easy-to-use analysis tools for use by electromagnetic compatibility engineers. These analysis tools consist of user-oriented computer programs written almost exclusively in the FORTRAN language. They can be applied to certain canonical problems to obtain results that can provide useful insight into related practical problems of interest.

As an example of the above, compatibility engineers have long been interested in determining the possible adverse effects of undesirable electromagnetic radiation on the performance characteristics of missiles in flight. Seeking to set up an appropriate experiment to study this problem a group of individuals working at the Redstone Arsenal and at the University of Mississippi used the method of moments to find the required separation distance of a given test antenna (that was to serve as a source of interference radiation) from the missile in order to simulate a free-space environment. In the process their analysis indicated that a thin missile having a major port of entry for interference signals at the dome or missile front-end could be most susceptible to interference signals approaching from the rear [1] (directions off the rear axis), a result which has been substantiated by subsequent investigations. This noteworthy conclusion resulted from modeling the missile as a relatively short thin wire irradiated by an electromagnetic wave - a canonical problem well-suited to analysis by the method of moments and a problem to which existing user-oriented computer programs based on the method of moments can be applied. Earlier results obtained by applying the method to a thin wire in a known incident field pointed to the same conclusion but they were not interpreted at the time in terms of a missile susceptibility problem [2]. The point to be made here is that the method of moments was applied in this instance to a simplified and manageable problem yielding results which provide useful insight into a difficult and complicated real-world problem.

Another interesting example of the use of the method of moments and its corresponding computational routines involves calculation of scattering (radar) cross-sections of electrically small aircraft. Just as with the missile example described above the actual aircraft is much too complex for an exact treatment by analytical techniques. Hence, approximate models are used that do lend themselves to theoretical and/or numerical solution. Lin and Richmond modeled a particular electrically small aircraft, the MIG 19, as a set of interconnecting wires irradiated by an electromagnetic wave [3]. This again is a configuration that is well suited to analysis by the method of moments and to treatment using existing user-oriented computer programs that are based on the method of moments. In this case the scattering cross-sections computed for the simplified thin-wire model provided considerable insight into the practical problem at hand, determination of the scattering behavior of the MIG 19.

The purpose of this report is to describe the method of moments briefly and to present and describe some of the most useful and readily available analysis tools (user-oriented computer programs) that are based on the method. The report is intended primarily for use by engineers working in the electromagnetic compatibility area. Emphasis is placed on describing the relative availability of the computer programs or codes that are discussed along with their ranges of applicability, inherent assumptions, limitations, existing applications and potential uses. Attention is limited to moment-method based computer programs suitable for a) treatment in the frequency domain and also in the time domain of problems involving the electromagnetic behavior of thin wires and rods, b) treatment in the frequency domain of problems involving radiation or scattering by two- and three-dimensional conducting bodies, c) problems involving the electromagnetic characteristics of two- and three-dimensional material bodies, again treated in the frequency domain, and d) frequency domain coupling of electromagnetic energy through apertures in conducting bodies.

2. FREQUENCY-DOMAIN, OR TIME-DOMAIN TREATMENT OF THE ELECTROMAGNETIC CHARACTERISTICS OF THIN WIRES AND RODS

2.1 Introduction

Over the past ten years or so a number of general user-oriented computer programs or codes have been developed to solve certain problems in the area of electromagnetics - in particular, problems of electromagnetic compatibility. These programs are capable of providing a variety of useful output quantities with only simple input data requirements. It is not necessary that the user know the detailed theory of the method of analysis used or the analytical details that were involved in writing the program since these are all packaged within the computer program itself. The user-oriented programs focused on in this report are those based on the general method of functional analysis known as the method of moments [4]. This method was specialized for problems of electromagnetics by Harrington who reported first results and observations in 1966 [5]-[7]. Harrington's work with the method of moments culminated in a unified treatment of matrix methods for fields problems which was presented in a (now) well-known and widely referenced paper [8] and again more completely in a later (1968) text [9].

The most frequent application of the method of moments has been for frequency domain treatment of problems involving analysis and design of radiation and scattering systems consisting of arbitrarily bent and interconnected thin wires and rods. It has been shown that for radiation problems the current distributions on the wires can be determined along with appropriate near- and far-field patterns and input admittances corresponding to feed points. For plane-wave scattering problems the current distributions again can be computed along with appropriate scattered fields and radar cross-section patterns. A given problem geometry can involve more than one wire and it is not necessary that all the wires have the same shape or even the same radius. Both discrete and distributed loading can be taken into account and the wires can be excited or fed at any arbitrary point or points along their lengths. Finally, since it is usually possible to include wire junctions in the problem geometry certain common configurations of practical interest can be handled such as wire crosses, supporting wires for long antennas, multielement networks, "stick" models of aircraft and missiles as mentioned earlier, and "wire grid" models of solid conducting bodies.

2.2 Method of Analysis for Wires

In the analysis procedure each thin-wire structure is treated basically as a multiport network. Port currents and voltages are related by a generalized impedance matrix which completely characterizes the wire structure and individual matrix elements are accurately computed using the method of moments. Radiation and retardation effects are taken completely into account, and no unrealistic assumptions are necessary regarding the current distributions of the wires.

Derivations of the integro-differential equations that are commonly used to characterize the current distributions of configurations of thin wires are available in the literature [8]-[12]. Here the term "thin wire" implies a wire of length L and radius a, where $L/a >> 1$ and $a << \lambda$, the wavelength. All wires are normally assumed to be perfect conductors, with wire losses treated as a special case of wire loading. The following approximations are usually made:

1. The currents are assumed to flow only in the axial direction.
2. The current and charge densities are approximated by filaments of current I and charge σ on the wire axes.
3. The boundary condition that the tangential component of the total electric field must be zero at any point on the surface of a conductor is applied only to the axial component of the electric field along each wire surface.

The method of moments serves to reduce the integro-differential equation that characterizes the wire current to a matrix equation. Approximate current distributions on the wires are obtained by solving this matrix equation using standard techniques. Then, once the current distribution is known, other parameters of engineering interest can be easily derived.

In applying the method of moments to thin-wire problems it is necessary to define a set of current expansion functions that can approximate the currents along the wires. Most user-oriented computer programs designed for treating such problems are based on one of four commonly used sets. These sets include a) pulse functions which result in a staircase approximation to each wire current, b) triangle functions which result in a piecewise linear approximation to each wire current, c) piecewise sinusoidal functions which result in a current approximation similar to the piecewise linear choice but which offer certain analytical advantages, and d) a set of three-term (constant, sine, and cosine) expansion functions which may again offer analytical advantages. In the paragraphs that follow, at least one readily available user-oriented computer program is discussed for each of the sets of current expansion functions mentioned.

2.3 User-Oriented Computer Program for Wires

A. Programs Based on Pulse Expansion Functions

The principles involved in using the method of moments are most easily explained in terms of their application to wires. At the same time, application of the method of moments to thin-wire problems is probably most easily explained in terms of the so-called "pulses and point-matching" solution. In this case each wire of a given problem geometry is considered as a number of short segments connected together as indicated in Fig. 1. The end points of each segment define a pair of terminals in space and these pairs are thought of as the ports of an M-port network. It is assumed the wires are thin and that current flows only in the axial direction. Current and charge densities are approximated by filaments of current I and charge on the wires axes. The boundary condition I = 0 at the ends of the wires is assured by using an extra half segment at each end of each wire as shown in Fig. 1. Thus, M represents the total

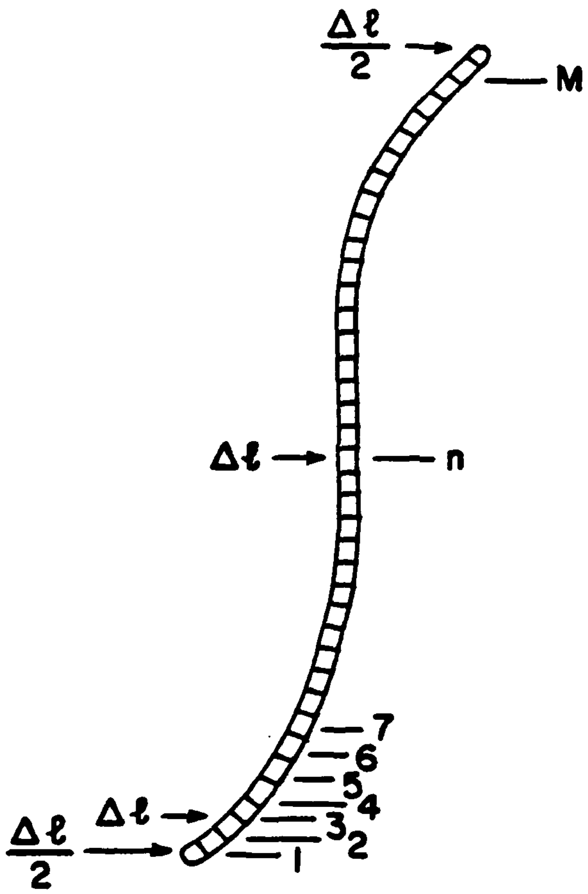
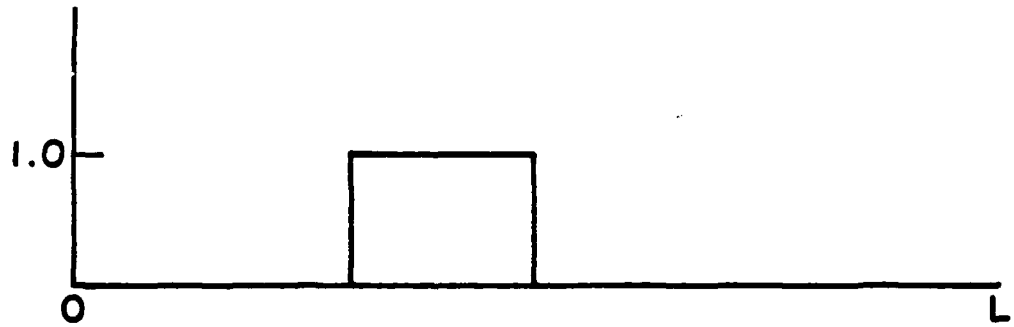


Fig. 1 - A thin wire divided into M+1 segments.

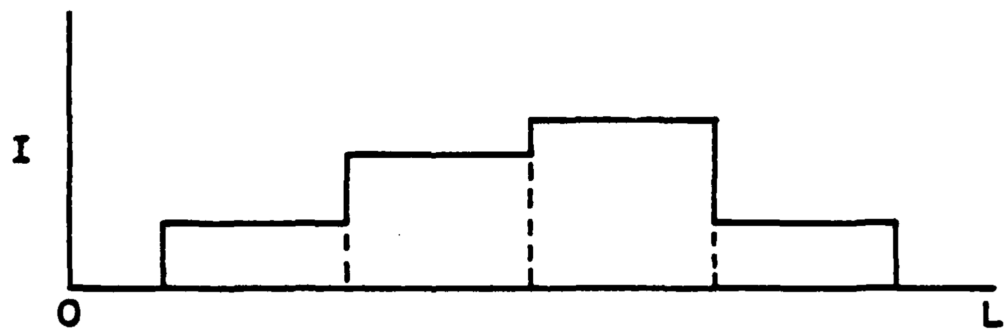
number of current carrying segments making up the wire configuration. As mentioned earlier the boundary condition regarding the tangential component of the electric field at the wire surfaces is satisfied (approximately) by requiring that the axial component vanish at the surface of each wire.

The current is expanded in a series of pulses, where each pulse is non-zero only over a single segment of one wire. The result is a staircase approximation for each wire current as shown in Fig. 2. The other possible choices for current expansion functions may have advantages over pulse functions with respect to accuracy and convergence. However, pulse functions are often used because they provide good engineering results and because they are easiest to deal with conceptually. Each pulse function is characterized by a complex number which represents the current amplitude over the corresponding segment. These numbers I(1) through I(M) are then arranged as a column matrix [I] which characterizes the current over the entire wire structure. Similarly, the applied excitation voltages, V(1),...,V(j),...,V(M) are arranged as a column matrix [V] where V(j) represents the excitation (in volts) applied at the jth segment. (One important advantage of the method described here is that radiation and scattering problems can be handled essentially in the same way. In scattering problems V(j) is proportional to the incident electric field over the corresponding segment. In radiation problems, of course, many of the applied excitation voltages are zero.) Thus

$$[I] = \begin{bmatrix} I(1) \\ I(2) \\ \vdots \\ I(M) \end{bmatrix} , \qquad [V] = \begin{bmatrix} V(1) \\ V(2) \\ \vdots \\ V(M) \end{bmatrix} \tag{1}$$



(a) Pulse function.



(b) Step approximation.

Fig. 2 - Pulse function and the step or staircase approximation of the current.

and

$$[V] = [Z][I] \tag{2}$$

where formulas [8,9] and corresponding computer programs are available for computing the self and mutual impedance elements of the generalized impedance matrix [Z]. This matrix completely characterizes the wire structure.

[Z] is a matrix of order M and is generally non-singular so that the current is given by

$$[I] = [Z]^{-1}[V] = [Y][V] \tag{3}$$

where [Y] is called the generalized admittance matrix. Once the voltage and current matrices are known it is a simple matter to obtain the input admittance at the pth feed point. That is

$$Y_{in}^{p} = \frac{I(p)}{V(p)} \tag{4}$$

Also, from [Y] the standard short-circuit admittance matrix $[Y_{sc}]$ can be found relating currents and voltages at the input ports. Thus, if the structure is excited with input voltages at ports (segments) i,j, k,ℓ,q then

$$\begin{bmatrix} I_i \\ I_j \\ I_k \\ I_\ell \\ I_q \end{bmatrix} = \begin{bmatrix} y_{ii} & y_{ij} & y_{ik} & y_{i\ell} & y_{iq} \\ y_{ji} & y_{jj} & y_{jk} & y_{j\ell} & y_{jq} \\ & & \cdot & & \\ & & \cdot & & \\ & & \cdot & & \\ y_{qi} & \cdot & \cdot & \cdot & y_{qq} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \\ V_k \\ V_\ell \\ V_q \end{bmatrix} \tag{5}$$

The admittance matrix in (5) is $[Y_{sc}]$ and its elements are identical with the corresponding elements of [Y]. It is important to note here that the open-circuit impedance matrix dual to $[Y_{sc}]$ cannot be found directly from [Z]. Rather, it is computed by simply inverting $[Y_{sc}]$.

In order to take wire losses and loading into account it is only necessary to add a load impedance matrix $[Z_\ell]$ to the generalized impedance matrix [Z]. $[Z_\ell]$ is a square $M \times M$ matrix and its only non-zero elements are on the diagonal. Thus, if segment n is loaded with some $Z_{\ell n}$ in ohms, then the nth term on the diagonal of $[Z_\ell]$ is $Z_{\ell n}$. Also, $[Z_\ell]$ has a zero on the diagonal corresponding to each unloaded segment. Finally, using a total generalized impedance matrix $[Z_T]$ where

$$[Z_T] = [Z] + [Z_\ell] \tag{6}$$

the current is found by replacing (3) with

$$[I] = [Z_T]^{-1}[V] \tag{7}$$

Once the current distributions on the various wires are known a variety of other quantities of interest can be computed easily. These include both near- and far-field patterns, radiation hazards, coupling and interference characteristics, receiving and scattering properties, and quantities pertaining to design and optimization.

While there are many user-oriented computer programs in existence that are based on the "pulses and point-matching" solution there are two in particular that are emphasized here because they are reasonably general and readily available. The first is the program WRSMOM that was created by individuals at RADC and Syracuse University, while the second is the computer code WF-SYR/LLL1 which was formulated by researchers at the Lawrence Livermore Laboratory. The term "pulses" refers to the method used for describing the current, while the expression "point-matching" implies that the boundary condition regarding the tangential component of the total electric field at the metallic wire surfaces is applied only at discrete points along the lengths of the wires. Important characteristics of these two user-oriented computer programs are pointed out in Tables 1 and 2 along with information concerning their availability. Some of the applications and potential uses of WRSMOM, WF-SYR/LLL1, and other "pulses and point matching" codes are pointed out in Section 2.5 of this report.

B. Program Based on Triangle Expansion Functions

Just as in the previous case the wires of a given configuration are thought of here as being divided into a number of short subsections or segments connected together. Each segment is defined by its two axial end points as depicted in Fig. 3. The complete set of points (together with the wire radii) essentially defines the geometry of the wire structure, and individual points are numbered consecutively from the first point of the first wire to the final point of the last wire. The spatial coordinates of these points are normally part of the required data input although they can be provided more easily for certain common configurations (loops, folded dipoles, etc.) by using generating functions.

When the current is expanded in triangle functions (such as the triangle in Fig. 4a) the result is a piecewise linear approximation to

TABLE 1 - PROGRAM WRSMOM

Authors:	D. E. Warren RADC/RBCT Griffiss AFB, N. Y. 13441 T. E. Baldwin Atlantic Research Corp. 5390 Cherokee Ave Alexandria VA 22314 A. T. Adams ECE Dept. 111 Link Hall, Syracuse University Syracuse, N. Y. 13210
Language:	FORTRAN IV
Application:	To configurations of straight thin wires
Purpose:	Computes current distributions, near electric and magnetic field distributions, far-field beam patterns, open-circuit impedance and short-circuit admittance matrices, coupling between pairs of feed ports, near field polarization ellipse parameters, and radiation hazard levels.
Features:	Wires of different radii are permitted; useful for antennas, scatterers, and arrays consisting of straight wires and rods that are electrically thin.

Limitations: Not intended for curved or bent wires; not intended for use with wire configurations containing junctions; wires are assumed to be isolated in free space and not acting in the presence of ground or obstacles (other than straight wires); only lumped impedance loading is permitted.

Availability: A brief program description appears in [13]. See NAPS document No. 02221 for 93 pages of supplementary material. Order from ASIS/NAPS c/o Microfiche Publications, P. O. Box 3513, Grand Central Station, New York, N.Y. 10017. Both microfiche and photocopies of supplementary material are available.

A manual entitled "A User Manual for Program WRSMOM" by D. E. Warren is available from the author.

TABLE 2 - PROGRAM WR-SYR/LLL1

Author:	R. M. Bevenesee Lawrence Livermore Laboratory P. O. Box 808 Livermore, California 94550 (415) 422-6787 Note: This program is a modified version of one presented earlier by H. H. Chao, D. C. Kuo, and B. J. Strait at Syracuse University. The program has been modified into a reconstructed version of a code developed at the Boeing Aerospace Company by W. L. Curtis.
Language:	FORTRAN IV
Application:	To arbitrary configurations of thin wires and to solid bodies modelled by a grid of interconnected thin wires.
Purpose:	Computes input impedances and input power along with current distributions for a configuration acting as an antenna. Program computes only the wire currents for scattering problems.
Features:	Useful for computing current distributions for a wide variety of wire configurations.

Limitations: Not as useful as WRSMOM for simple configurations such as an array of straight wires; only one wire radius is permitted; wires are assumed to be isolated in free space and not acting in the presence of ground or obstacles (other than other additional wires); program does not compute field distributions; only lumped impedance loading is permitted.

Availability: A brief program description appears in [14]. User's manual and card deck are available from Dr. Bevensee at the Lawrence Livermore Laboratory [70].

the current as indicated in Fig. 4b. Each triangle extends over

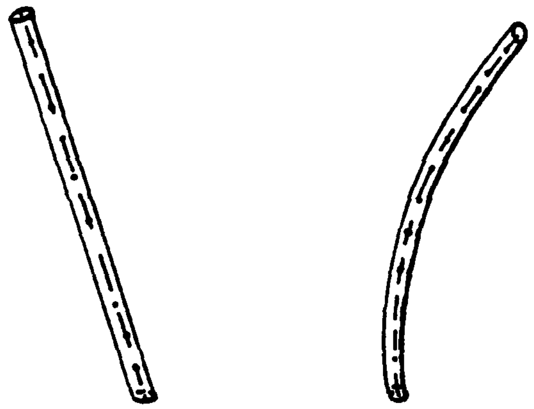
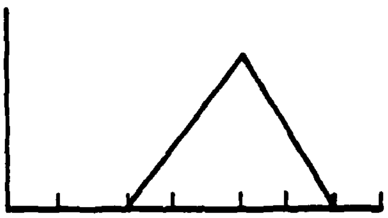


Fig. 3. Problem geometry specified by a sequence of points together with wire radii.



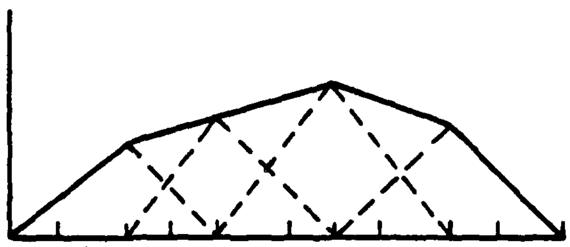


Fig. 4a. Triangle function. Fig. 4b. Piecewise linear approximation.

four adjacent segments and is defined by five consecutively numbered points. It is evident that an odd number of points is required to specify the geometry of each wire, although the total number of points for the entire problem may be even. In the program described here feed voltages and load impedances can only be applied at wire positions corresponding to the peaks of triangles. However, this does not detract from the program generality in any way because the points (and hence, the segments) can always be specified such as to locate feeds and loads at any desired wire positions. Thus, if there are NP points defining the geometry of a single wire then there are (NP-1) segments and $(\frac{NP-1}{2} - 1)$ or M expansion functions. Finally, either feed voltages or load impedances can be applied at any of the $(\frac{NP-1}{2} - 1)$ triangle peaks.

As before, the current is expressed as a sequence of complex numbers, each representing the amplitude of its corresponding expansion function (triangle in this case). These numbers are arranged as a column matrix of dimension M where M is the total number of expansion functions used. This current matrix [I] is related to the excitation voltages applied to the wire structure by (3) where [V] is a column matrix of M excitation voltages and [Z] is the generalized impedance matrix whose elements are calculated by the method of moments. A typical element of [V], say V_i, is the complex excitation voltage applied at a position corresponding to the peak of the ith triangle function. If no excitation is applied at that point then the corresponding element of [V] is zero. As mentioned above this actually allows excitation voltages to be applied at arbitrary points on the wire structure since both the number of expansion functions and the lengths of the individual segments used can be selected by the program user. Wire loading is handled in a manner identical to that described earlier allowing impedance loads to be applied at wire positions corresponding to the peaks of the triangle functions. The typical element $(Z_\ell)_{jj}$ of the diagonal load impedance matrix $[Z_\ell]$ is the complex load impedance in ohms placed at a wire position corresponding to the peak of the jth triangle function. Of course, if the wire structure is unloaded at that point then $(Z_\ell)_{jj}$ is zero. Thus, given the excitation voltages and load impedances, the current distribution for a given problem is computed using (3) or (7). Then, once the current is known other quantities of interest such as input impedances or field patterns can be calculated easily using standard formulas and techniques. The excitation voltages for scattering problems are calculated from the incoming wave specified by the user as before.

The computer program WIRES is a readily-available user-oriented code based on the piecewise linear current described in this section. This program was written specifically to handle general wire configurations including junctions. For radiation problems the current distributions on the wires are calculated along with appropriate input impedances, far-field patterns and near-field distributions. For scattering problems the current is again computed along with specified scattered field and radar cross-section patterns. Important characteristics of WIRES are pointed out in Table 3 along with information concerning its availability. Some of the applications and potential uses of WIRES are pointed out in Section 2.5 of this report.

TABLE 3 - PROGRAM WIRES

Authors:	D. C. Kuo H. H. Chao J. R. Mautz B. J. Strait R. F. Harrington ECE Dept. 111 Link Hall, Syracuse University Syracuse, N. Y. 13210
Language:	FORTRAN IV
Application:	To radiation and scattering by arbitrary configurations of thin wires and to solid bodies modelled by grids of interconnected thin wires.
Purpose:	For radiation problems the current distributions on the wires are computed along with specified near field distributions, radiation patterns, and input admittances at feed points. For plane-wave scattering problems the current distributions are again computed along with specified scattered field and radar cross-section patterns.
Features:	Designed specifically for problems involving junctions. Arbitrary discrete excitation and loading are permitted. Changes in wire radii are permitted.

Limitations: WIRES is intended to handle general wire configurations. Hence, when problems are encountered that are characterized by certain symmetries WIRES may require more time for solutions than required by programs dedicated to such problems. A linear array of parallel and identical straight wires is one such case.

The wires are assumed to be isolated in free space and not acting in the presence of ground or obstacles (other than additional wires). Only discrete excitation and loading are permitted. However, special subroutines permitting distributed excitation and loading can be obtained from the authors.

Availability: A brief program description appears in [15]. See NAPS document No. NAPS-01798 for supplementary material. Order from ASIS/NAPS, c/o Microfiche Publications, P. O. Box 3513, Grand Central Station, New York, N.Y. 10017. Both microfiche and photocopies of supplementary material are available.

An independent description of WIRES (also called WF-SYR) is given in [16]. Original descriptions of the program are contained in research reports [17]-[19]. A brief description for users is available in [20].

Individuals using the code should take advantage of a program correction suggested by Tew [21] which has been included in [16] but not [15] as of this date.

Card decks for the corrected program are available from the authors at Syracuse University. A modified listing and source deck for WF-SYR as run on the CDC 7600 are available from the Electromagnetic and System Research Group at the Lawrence Livermore Laboratory.

The WIRES program has been modified for treatment of arbitrary configurations of thin-wire antennas and scatterers acting in the presence of an imperfectly conducting half-space (ground). See Section 2.5 of this report.

C. Program Based on Piecewise Sinusoidal Functions

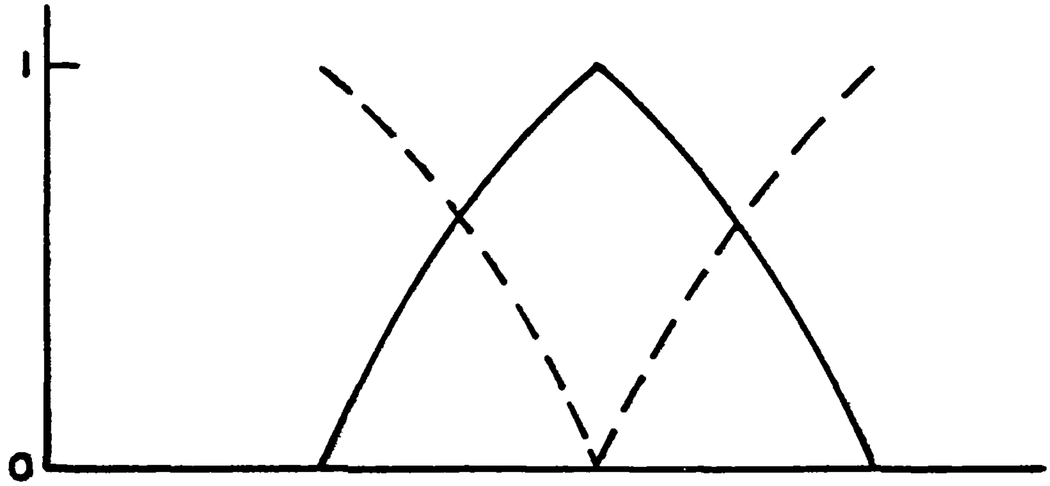
Once again each wire of the given configuration is divided into a number of short segments or subsections. The current expansion functions are piecewise sinusoidal functions as originally suggested by Richmond [22] [23]. A typical expansion function can be expressed analytically as (for a z-directed wire and $k = \frac{2\pi}{\lambda}$)

$$\vec{I}_n(z) = \hat{u}_z \frac{\sin k(z - z_{n-1})}{\sin k(z_n - z_{n-1})} \qquad z_{n-1} \leq z < z_n$$

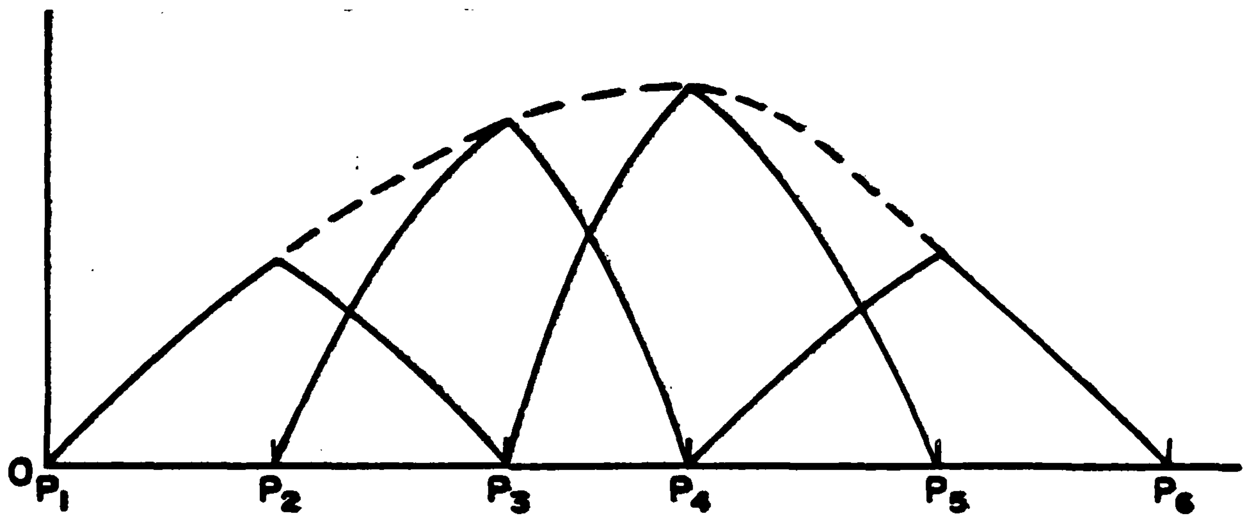
$$= \hat{u}_z \frac{\sin k(z_{n+1} - z)}{\sin k(z_{n+1} - z_n)} \qquad z_n \leq z < z_{n+1} \tag{8}$$

and is depicted in Fig. 5.

A readily-available user-oriented computer program that uses this current approximation has also been presented by Richmond [24]. The program entitled "Sinusoidal Reaction for Thin Wires" appears to have received the greatest level of general acceptance among users of any of the programs suggested in this report. Within the program the matrices [I], [V], and [Z] have the same definitions as before. Elements of the column matrix [I] are complex amplitudes of the corresponding piecewise sinusoidal current expansion functions. Elements of the generalized impedance matrix [Z] are interaction terms representing relationships between excitations and responses at different points along the wire configuration. For radiation problems excitations are assumed to be applied only at wire positions corresponding to the peaks of current expansion functions. Hence, just as with the program



(a) PIECEWISE SINUSOIDAL FUNCTION.



(b) PIECEWISE SINUSOIDAL CURRENT APPROXIMATION.

Fig. 5 - Current expansion for Richmond's program.

based on piecewise linear functions, each element of [V] is the complex excitation voltage applied at the wire position marking the peak of the corresponding expansion function. Obviously, for many radiation problems most elements of [V] are zero. For scattering problems elements of [V] are calculated within the program from the incoming wave specified by the program user. The matrices [V], [I], and [Z] are again related as in (3). Lumped impedance loading is also handled as before with loads applied only at wire positions corresponding to the peaks of current expansion functions. A diagonal load impedance matrix $[Z_L]$ is added directly to [Z] and the current is obtained using (6) and (7) rather than (3).

Richmond's original code was designed to handle radiation and scattering problems of arbitrary thin-wire configurations in a homogeneous conducting medium. Wires may have finite conductivity, lumped loads, and lossy insulation. The surrounding medium may be a lossy dielectric. Required input data include the operating frequency, wire radius, wire conductivity, parameters of the surrounding medium, spatial coordinates of points that describe the shape and size of the wire configuration, and parameters of the wire insulation sleeve. For radiation problems output data include current distribution, input impedances corresponding to feed points, radiation efficiency, gain, radiation field patterns, and near-field distributions. For scattering problems the output includes the echo area and the polarization scattering matrix. For backscatter problems the output also includes the absorption, scattering, and extinction cross-sections.

Important characteristics of Richmond's program are summarized in Table 4 along with information concerning its availability. Some of its applications and potential uses are pointed out in Section 2.5 of this report. At least two additional readily available and user-oriented codes have been devised through modification of Richmond's work. One of these is the code entitled ASAP written by McCormack and Adler at the Naval Postgraduate School in Monterey, California to handle problems of radiation and scattering by wire structures acting in the presence of an imperfectly conducting half space (ground) [25]. Their program has received an independent study and evaluation by individuals at the Lawrence Livermore Laboratory who refer to the code as WF-OSU/NPS1 [26]. Certain characteristics of this program are summarized in Table 5 of this report along with information pertaining to its availability. Richmond also presented a modified version of his code to handle radiation by wire antennas situated over perfectly conducting ground [28]. This in turn was extended by Bevensee for treatment of both radiation and scattering by wires in the presence of perfectly conducting ground [26]. The wires may even touch ground at one or more places. These modified programs are somewhat reduced in general capability as compared with Richmond's original code although as mentioned they do offer the special capability of allowing analysis to include the effects of the perfectly conducting plane.

TABLE 4 - SINUSOIDAL REACTION FOR THIN WIRES

Author:	J. H. Richmond ElectroScience Laboratory Department of Electrical Engineering Ohio State University Columbus, Ohio 43212
Language:	FORTRAN IV
Application:	To radiation and scattering by arbitrary configurations of thin insulated or uninsulated wires and to solid bodies modelled by grids of interconnected thin wires.
Purpose:	For radiation problems the current distributions on the wires are computed along with radiation patterns, near fields, input impedances corresponding to feed points, gain, and radiation efficiency. In bistatic scattering problems the output includes the echo area and the complex elements of the polarization scattering matrix. In backscattering problems the output includes also the absorption, scattering, and extinction cross-sections.
Features:	Handles problems involving wire junctions well. Lossy surrounding medium is permitted as well as lossy sleeve insulation. Finite wire conductivity is allowed along with discrete excitation and loading.

Limitations: Changes in wire radius are not permitted. The wires are assumed to be isolated in an homogeneous surrounding medium and not acting in the presence of obstacles (other than additional wires that can be included in the analysis).

Availability: A brief program description appears in [24]. See NAPS document No. NAPS-02223 for supplementary material. Order from ASIS/NAPS c/o Microfiche Publications, P. O. Box 3513, Grand Central Station, New York, N.Y. 10017. Both microfiche and photocopies of supplementary material are available.

An independent description of this program (also called WF-OSU) is given in [27].

TABLE 5 - PROGRAM ASAP

Authors:	J. W. McCormack R. W. Adler Naval Postgraduate School Monterey, California 93940
Language:	FORTRAN 4
Application:	To radiation and scattering by arbitrary configurations of thin insulated or uninsulated wires acting in the presence of an imperfectly or perfectly conducting half-space (ground).
Purpose:	Computational objectives and output are the same as those described in the program of Table 4 except that in this case a perfectly conducting or imperfectly conducting ground can be included in the calculations.
Features:	Special features are those given with the program of Table 4 in addition to the special ground capability of ASAP.
Limitations:	Changes in wire radius are not permitted. Effects of imperfect ground are included by way of the "method of reflection coefficients," so that accuracy of results for near fields and currents at points near ground is reduced.

Availability: User's manual, program listing, and supplementary material are available in [25]. An independent description and evaluation of the code (also denoted by WF-OSU/NPS1) was performed by individuals at the Lawrence Livermore Laboratory, Livermore, California, and is available in [26].

D. Program Based on Three-Term Sinusoidal Functions

The readily available user-oriented computer program WAMP is the last of the thin-wire codes to be discussed in this report. This also takes a segmented or subsectional approach with a typical current expansion function (nth expansion function) given by (for a z-directed wire with its nth segment centered at point z_n)

$$\vec{I}_n(z) = \hat{u}_z[A_n + B_n \sin k(z-z_n) + C_n \cos k(z-z_n)] \tag{9}$$

This differs noticeably from the previous choices in that each expansion function involves three complex constants rather than just one. It turns out, however, that two of the three constants are determined by extrapolation to the center points of adjacent segments and matching current values as described by different expansion functions at those center points. The result is that a matrix equation similar to (3) is again solved to obtain the unknown current matrix [I] or one similar to (7) if the wires are subjected to impedance loading. The matrix [Z] as usual is calculated within the program by way of the method of moments and elements of [V] are specified by the user. WAMP is intended for radiation problems only.

The code WAMP is a derivative of an earlier program called BRACT developed by MB Associates of San Ramon, California. Modifications of the program into the form reported here were made by Miller and Deadrick of the Lawrence Livermore Laboratory [16] [29]. WAMP was written to handle radiation by thin-wire structures acting either in free space or in the presence of an imperfectly conducting half-space (ground). The effects of ground are included in the analysis by way of the method of reflection coefficients. A radial wire ground screen can be included in parallel with the normal ground medium. Excitation and impedance loading capabilities are quite general. Computed output includes near-field distributions, radiation patterns, current distribution and input impedances corresponding to feed points. Essential characteristics of WAMP are summarized in Table 6 of this report together with information pertaining to its availability.

WAMP is also denoted by its authors at the Lawrence Livermore Laboratory as WF-MBA/LLL1. Two derivatives of WAMP are the programs WF-LLL2A and WF-LLL2B authored by Lager and Lytle of the Lawrence Livermore Laboratory [30]. Essentially these are both designed to handle radiation from wire structures in free space or in the presence of a lossy half-space, including structures penetrating the interfaces. These programs are very general in that they enable treatment of the imperfect ground effects by any one of four possible procedures. The first two of these procedures are basically the reflection coefficient technique contained in WAMP. The third, more rigorous approach is the use of Norton's formulas when the distances and ground parameters involved are within the proper range. The fourth and most rigorous procedure involves use of two representations of the Sommerfeld integrals. Details of these procedures are, of course, contained within the computer programs involved and are available in the literature [30]-[32]. Characteristics of these programs are described briefly in Table 7 of this report along with information pertaining to their availability.

TABLE 6 - PROGRAM WAMP

Authors:	E. K. Miller F. J. Deadrick Lawrence Livermore Laboratory P. O. Box 808 Livermore, California 94550
Language:	FORTRAN IV
Application:	To radiation by arbitrary configurations of thin wires in free space or acting in the presence of an imperfectly conducting half-space.
Purpose:	Computes current distributions, input impedances corresponding to feed points, radiation patterns, and near-field distributions.
Features:	Effects of imperfect ground are accounted for in the analysis by using the (approximate) method of reflection coefficients. Configurations may include junctions and wires of different radii. A radial ground screen can be included in parallel with the normal ground medium. Essentially arbitrary discrete excitation and loading are permitted. Perfectly conducting ground can also be treated.

Limitations: Intended for radiation problems only. Results may be in error when structures are close to the ground surface.

Availability: A users manual for WAMP is available [29]. A brief description of the code also referred to as WF-MBA/LLL1 appears in [16]. A source deck and users manual can be obtained from the Electromagnetics and Systems Research Group at the Lawrence Livermore Laboratory.

TABLE 7 - PROGRAMS WF-LLL2A AND WF-LLL2B

Authors:	D. L. Lager R. J. Lytle F. J. Deadrick E. K. Miller Lawrence Livermore Laboratory P. O. Box 808 Livermore, California 94550
Language:	LLLTRAN (a FORTRAN language implemented by the Computations Department at the Lawrence Livermore Laboratory).
Application:	To radiation and scattering from wire structures in free space or acting in the presence of a lossy half-space, including structures penetrating the interface.
Purpose:	Computes current distributions, input impedances, and far-field radiation patterns (including surface-wave fields).
Features:	Incorporates four methods for treating the effects of imperfect ground. Configurations may involve junctions, wires of different radii, and essentially arbitrary excitation and loading. Perfectly conducting ground can also be treated.

Limitations: These programs may not be efficient choices for simple canonical problems such as those involving single straight wires.

Availability: User's manual with program listings is available in [30]. A brief description is given in [26]. Listings and source decks can be obtained from the Electromagnetics and Systems Research Group at the Lawrence Livermore Laboratory.

2.4 Summary

In this chapter the existence of several user-oriented computer programs suitable for frequency-domain treatment of radiation and scattering by thin wires and rods has been pointed out. All of these can be described or interpreted in terms of the method of moments. Although all of these codes are quite general, each one has certain advantages over the others for some problems and disadvantages with respect to the other codes for other problems. For example, WRSMOM is not intended for problems with wires acting over imperfect ground, but it is particularly useful for an array of parallel wires acting in free space. No attempt is made here to compare these codes as to their relative applicability and accuracy for various classes of problems, although several useful comparisons have been performed by other researchers [11], [12], [33]-[39]. The objective here is simply to point out some of the most user-oriented and readily available programs that have been found helpful by researchers in the areas of electromagnetics and electromagnetic compatibility. Some of their uses and potential applications are pointed out in the next section.

2.5 Applications of the User-Oriented Programs

In this section certain applications of the user-oriented computer programs designed for frequency-domain treatment of thin-wire structures are pointed out. The most straightforward canonical problems are listed first with typical results. These are followed by references to treatments of more complicated practical problems.

1. Radiation or Scattering in Free Space by a Single Thin Wire

Computed results for radiation and scattering by a single thin-wire antenna with or without impedance loading and acting in free space are plentiful. These are useful for checking the operation and accuracy of any program when its use is initiated and for studying convergence characteristics with respect to the number of current expansion functions that should be used. Typical results are shown in Figs. 6-17. In each case the type and number of current expansion functions used are given along with a reference to the original report or document from which the result was taken. Other useful results for problems of this type are available in [2], [41]-[46]. Experimental results are also available for comparisons [47], [48].

Generally speaking the user-oriented computer programs described in this report can handle analysis of monochromatic free-space radiation and scattering by single thin wires of arbitrary shape and with arbitrary excitation and loading. For radiation problems the analysis yields current distributions, near-and far-field patterns and input impedances corresponding to feed points. For scattering problems the current distributions are again calculated along with scattering cross-section parameters and patterns of interests.

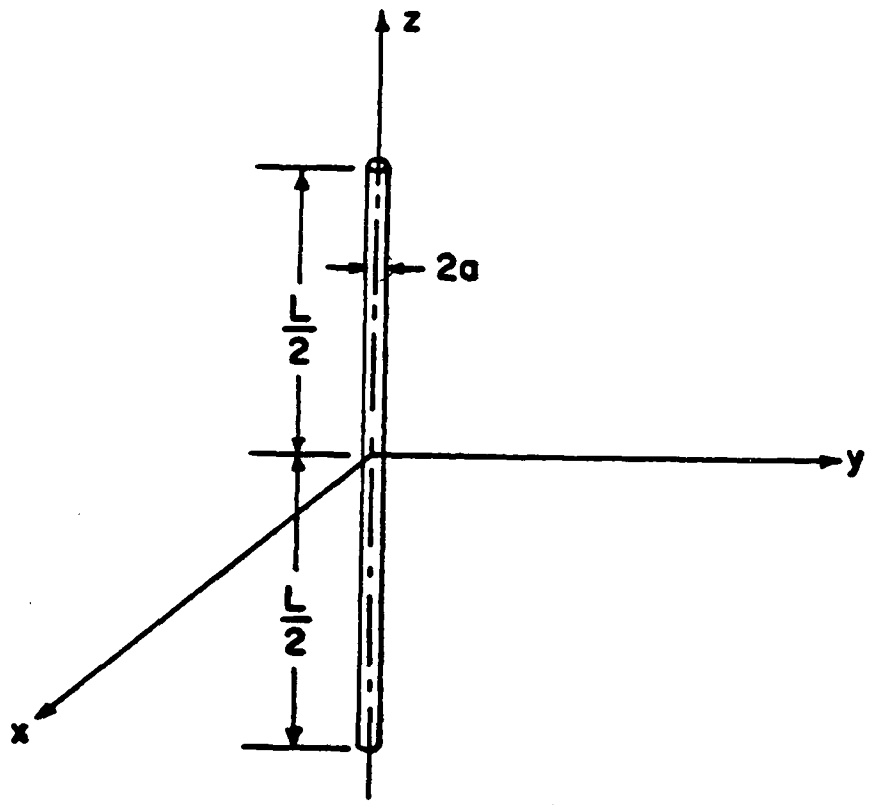


Fig. 6 - Straight wire and coordinate system.

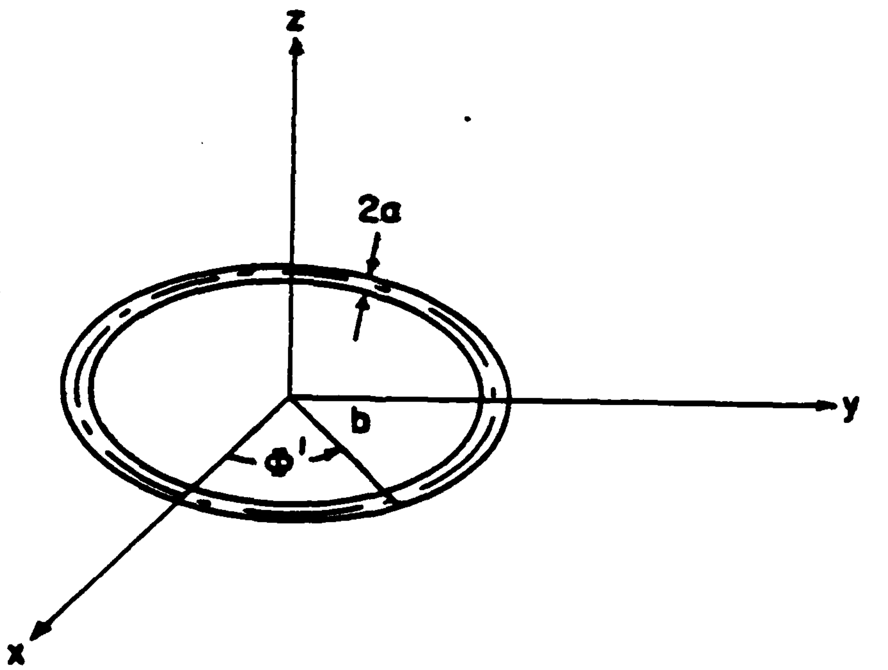


Fig. 7 - Circular-loop and coordinate system.

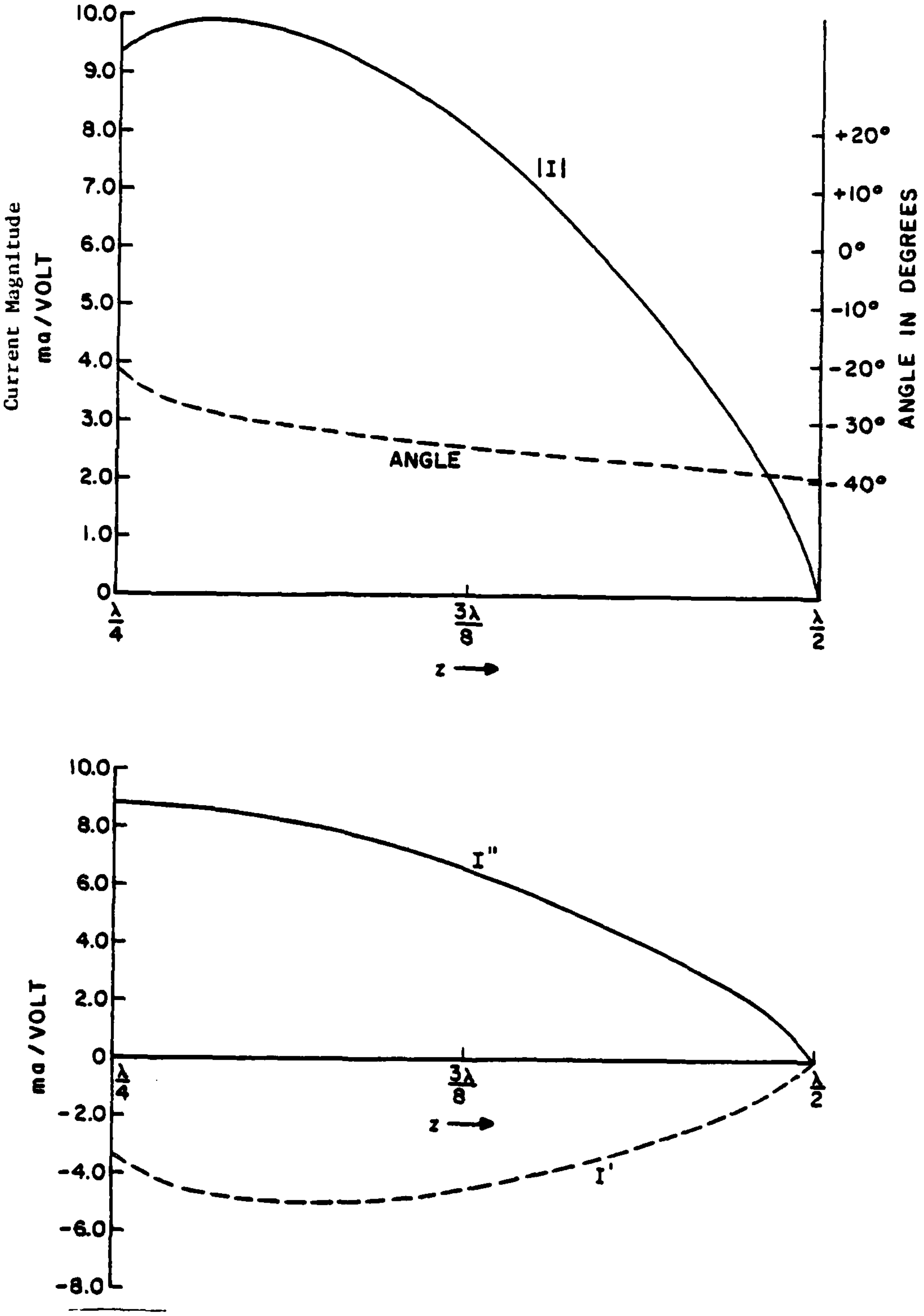


Fig. 8 - Current on a half-wave wire that is centerfed with a unit voltage. $I = I'' + j\,I'$. Pulse expansion functions [40] [57]. $M = 23$. $2\pi a = 0.04412\lambda$.

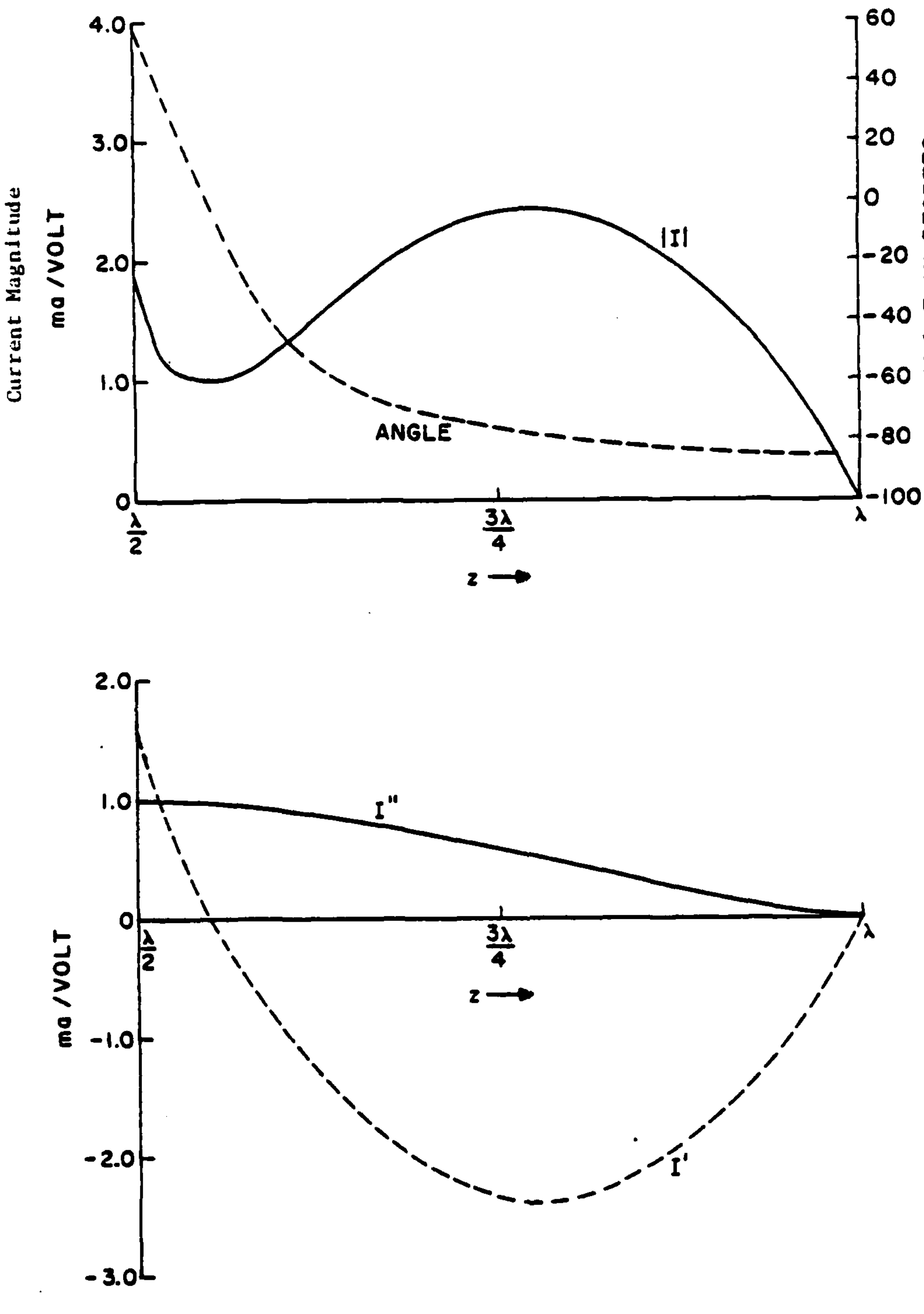


Fig. 9 - Current on a full-wave wire that is centerfed with a unit voltage. $I = I'' + j\,I'$. Pulse expansion functions [40] [57]. $M = 23$. $2\pi a = 0.04412\lambda$.

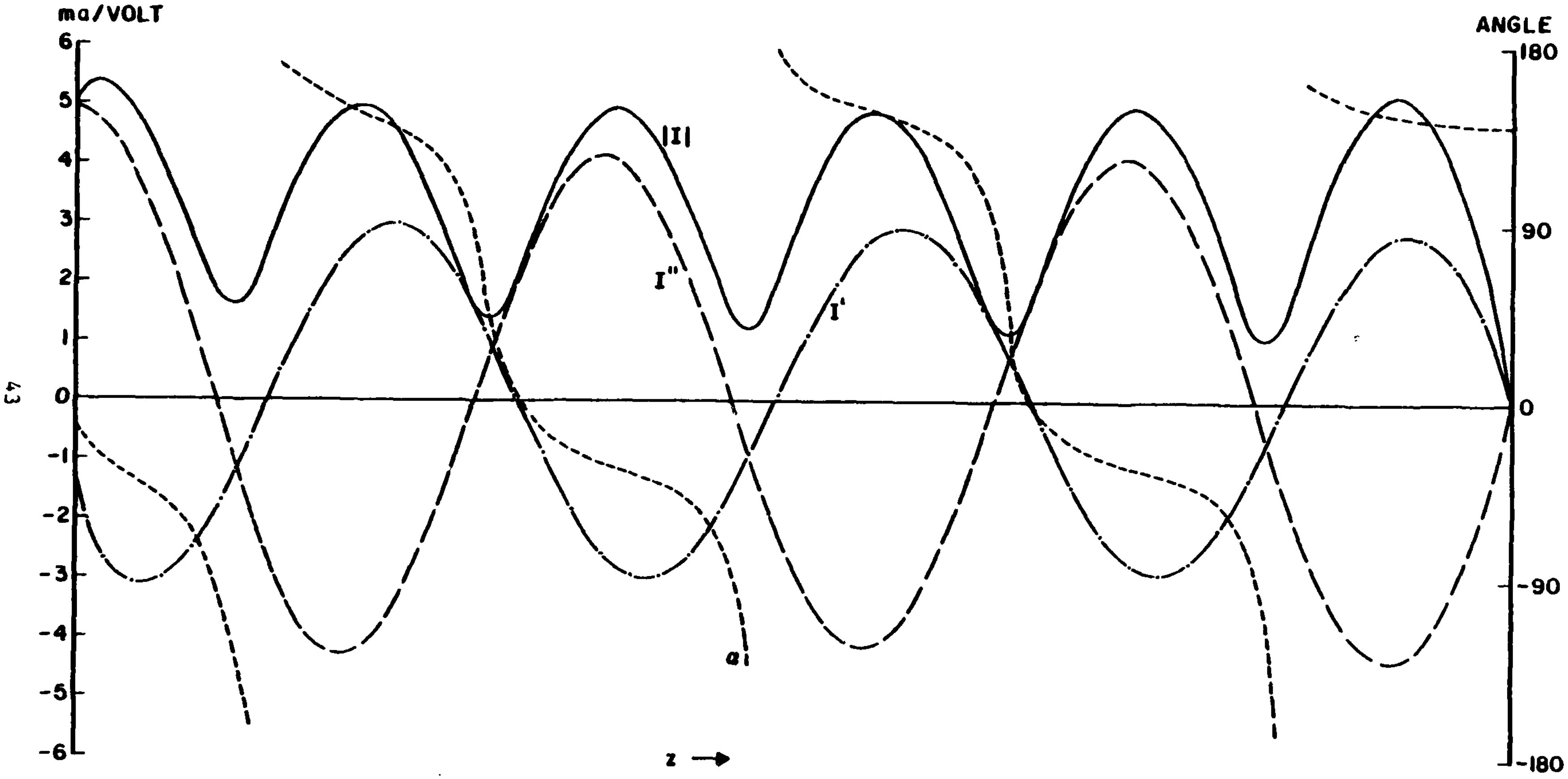


Fig. 10 - Current distribution on a 5 1/2 - wavelength wire that is centerfed with a unit voltage. $I = I'' + j\,I' = |I| \angle \alpha$. Pulse expansion functions [40] [57]. $M = 97$. $2\pi a = 0.0399\lambda$.

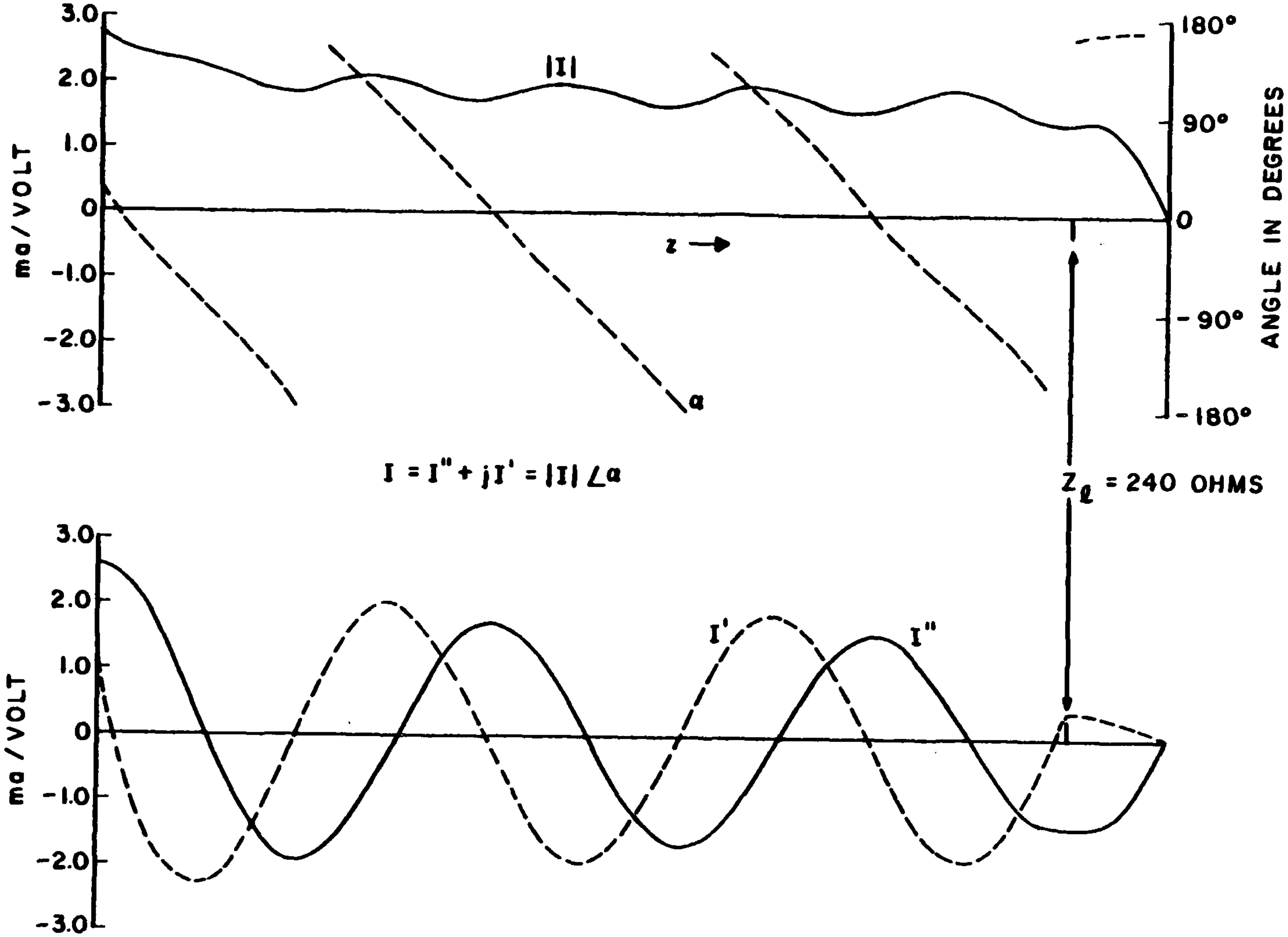


Fig. 11 - Current distribution on a 5 1/2-wavelength wire that is centerfed with a unit voltage. The wire is loaded symmetrically with Z_{ℓ} = 240 ohms as shown. Pulse expansion functions [40] [57]. $M = 65$. $2\pi a = 0.0399\lambda$.

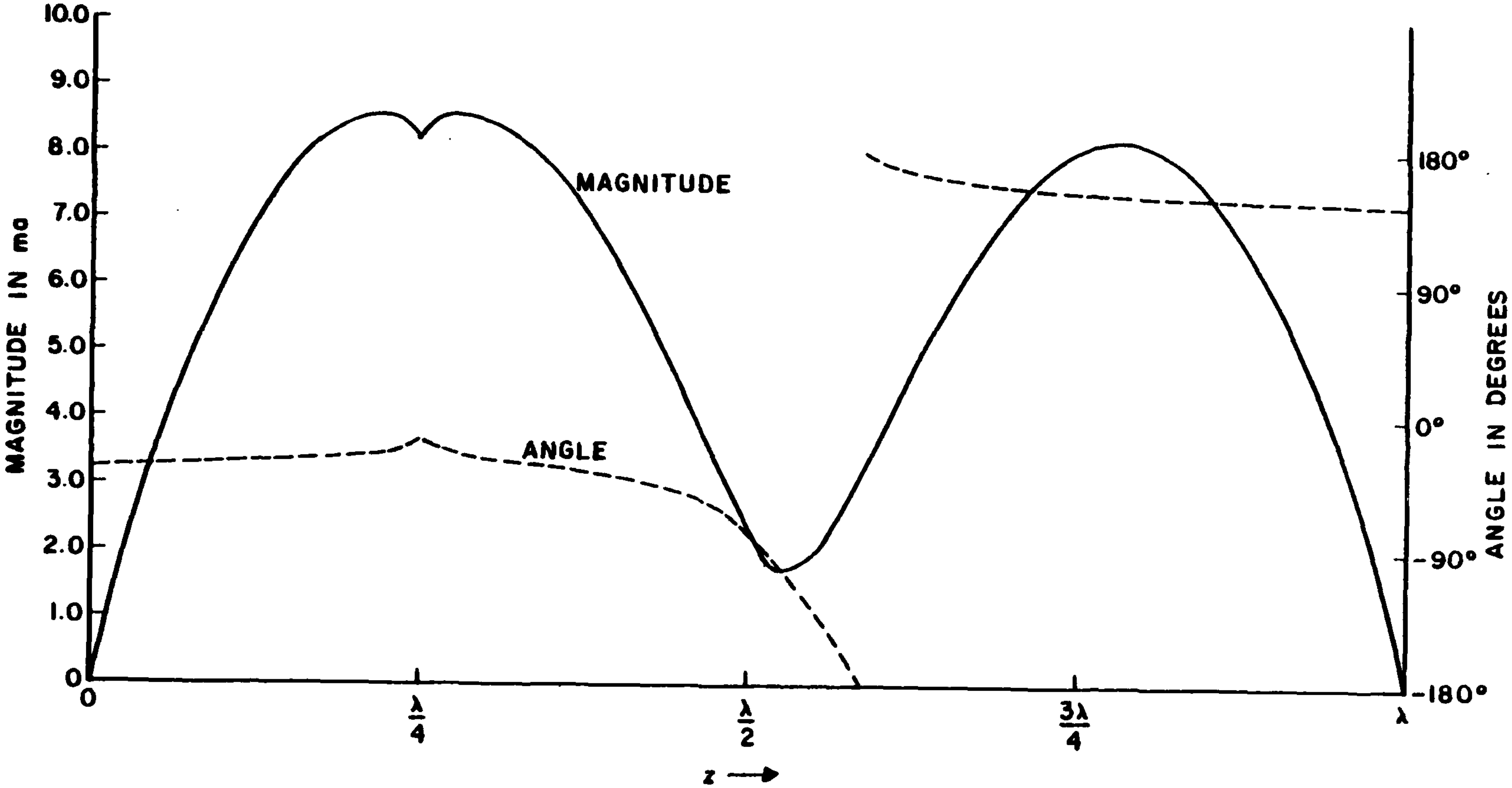


Fig. 12 - Current (magnitude and phase) on a full-wave wire due to a unit voltage source at $z = \lambda/4$. Pulse expansion functions [40] [57]. $M = 19$. $2\pi a = 0.04234\lambda$.

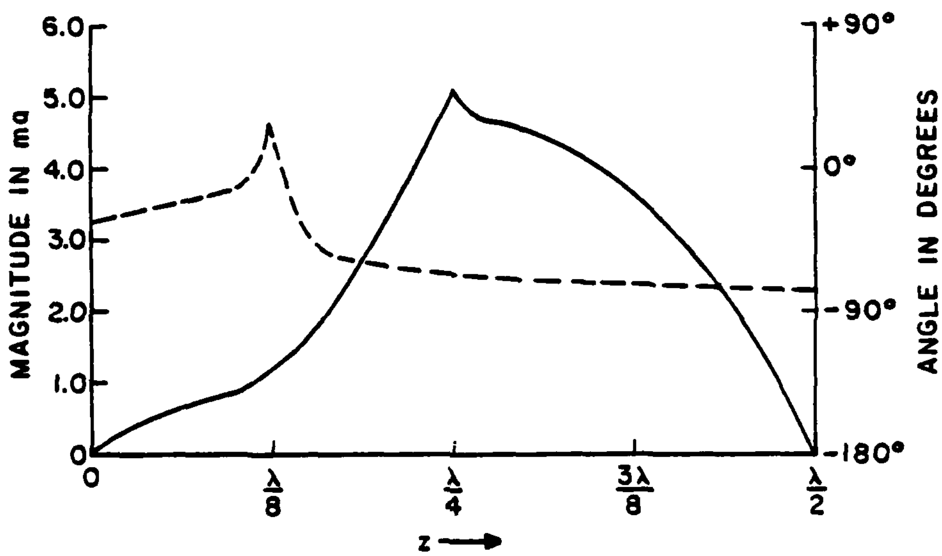


Fig. 13 - Current (magnitude and phase) on a loaded half-wave wire due to a unit voltage source at $z = \lambda/8$. $Z_L = j100$ at $z = \lambda/4$. Pulse expansion functions [40] [57]. M = 39. $2\pi a = 0.04234\lambda$.

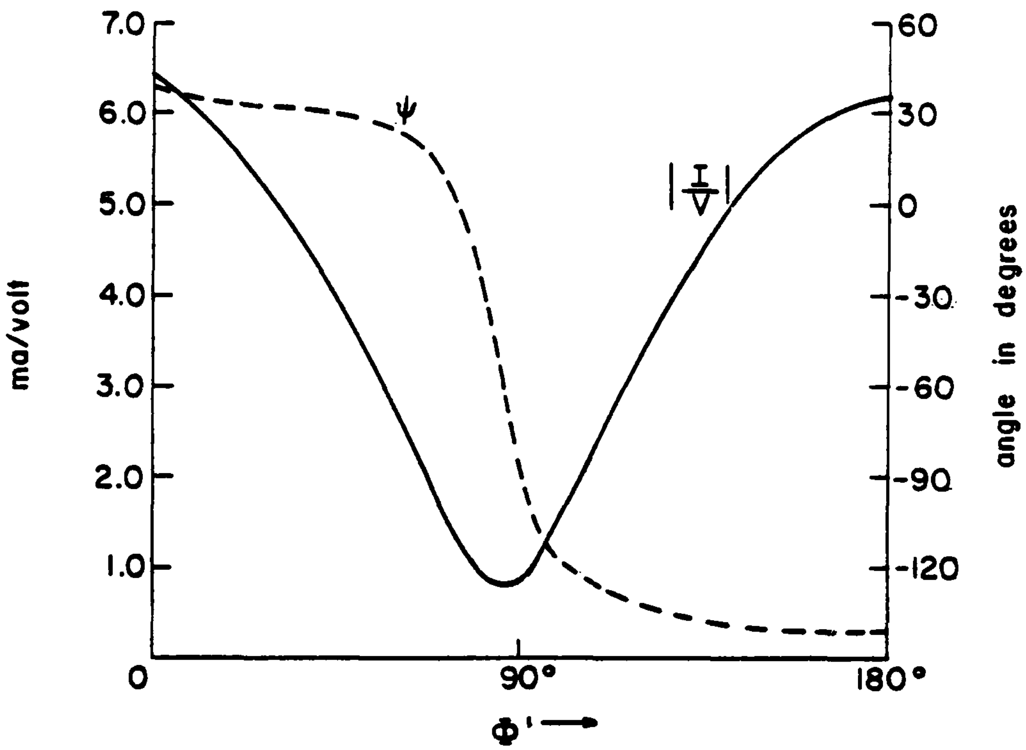


Fig. 14. Current on a circular loop antenna with circumference $2\pi b=\lambda$. $a = 0.00106\lambda$ (λ = 1 meter). Excitation of one volt at $\phi' = 0$. Triangle expansion functions [17] $M = 16$.

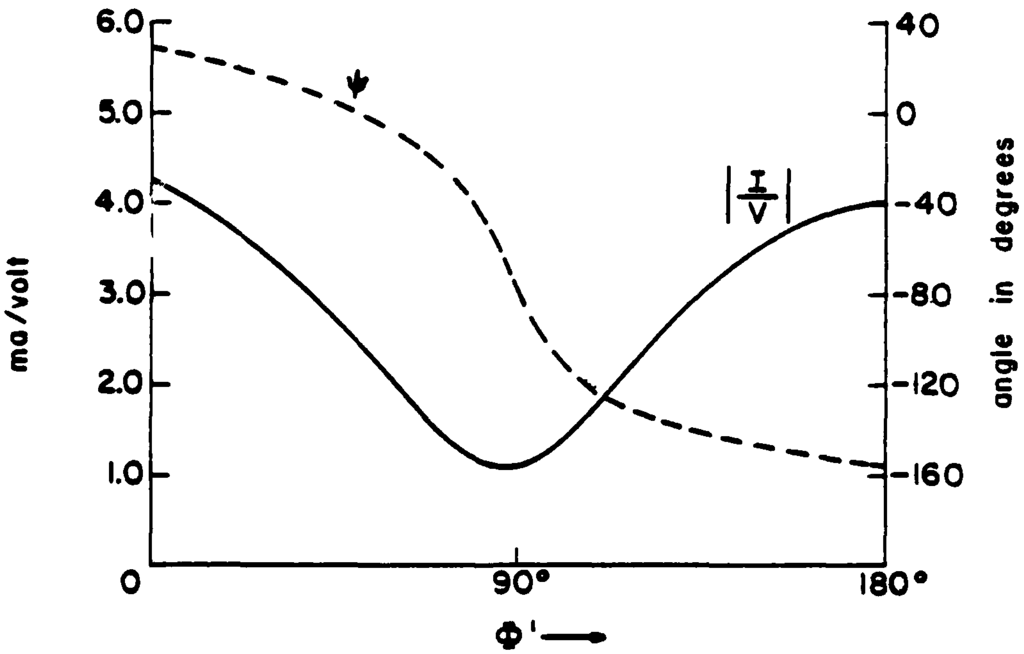


Fig. 15. Current on a loaded circular loop antenna with circumference $2\pi b=\lambda$. $a = 0.00106\lambda$ (λ = 1 meter) Excitation of one volt at $\phi' = 0$. Load $Z_\ell = 100$ at $\phi' = 180°$. Triangle expansion functions [17] $M = 16$.

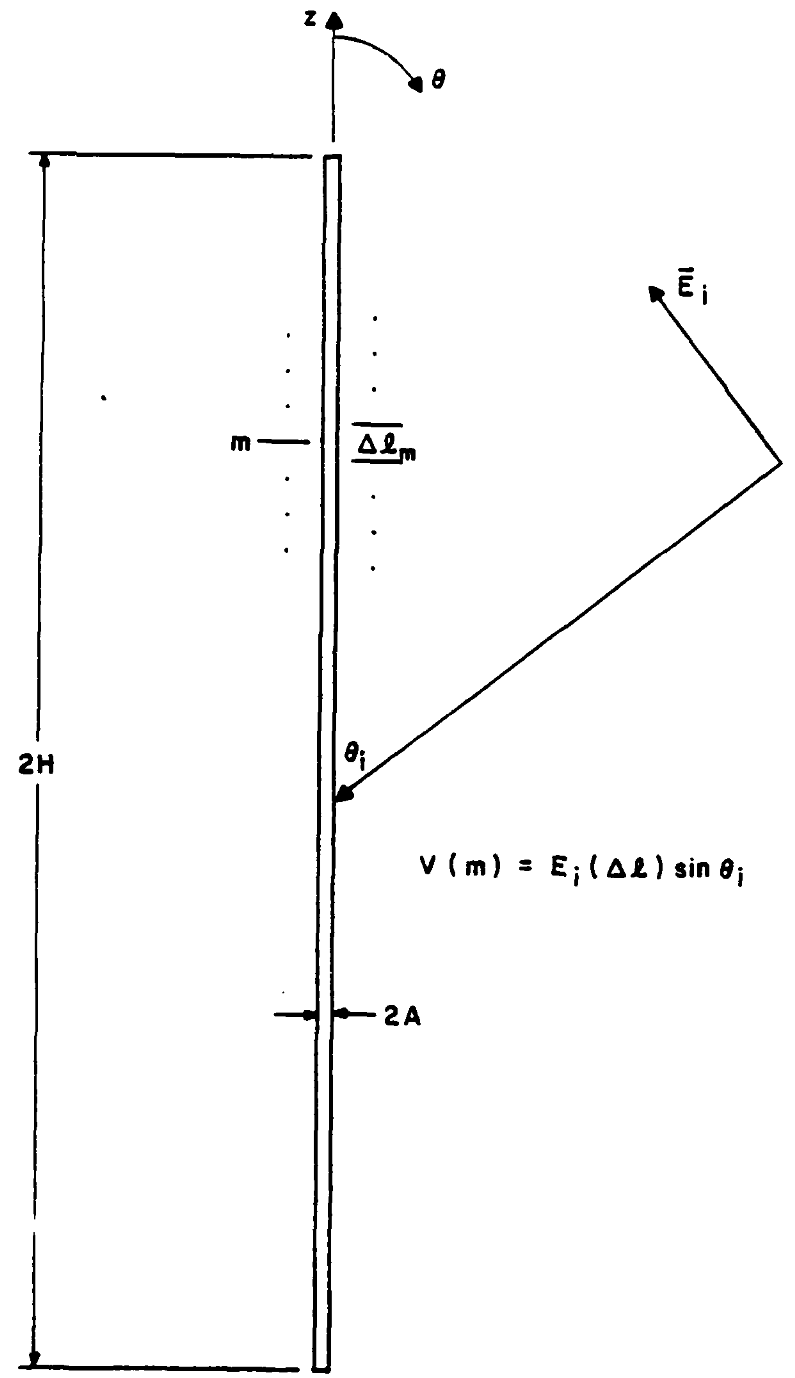


Fig. 16 - A thin wire irradiated by a plane electromagnetic wave.

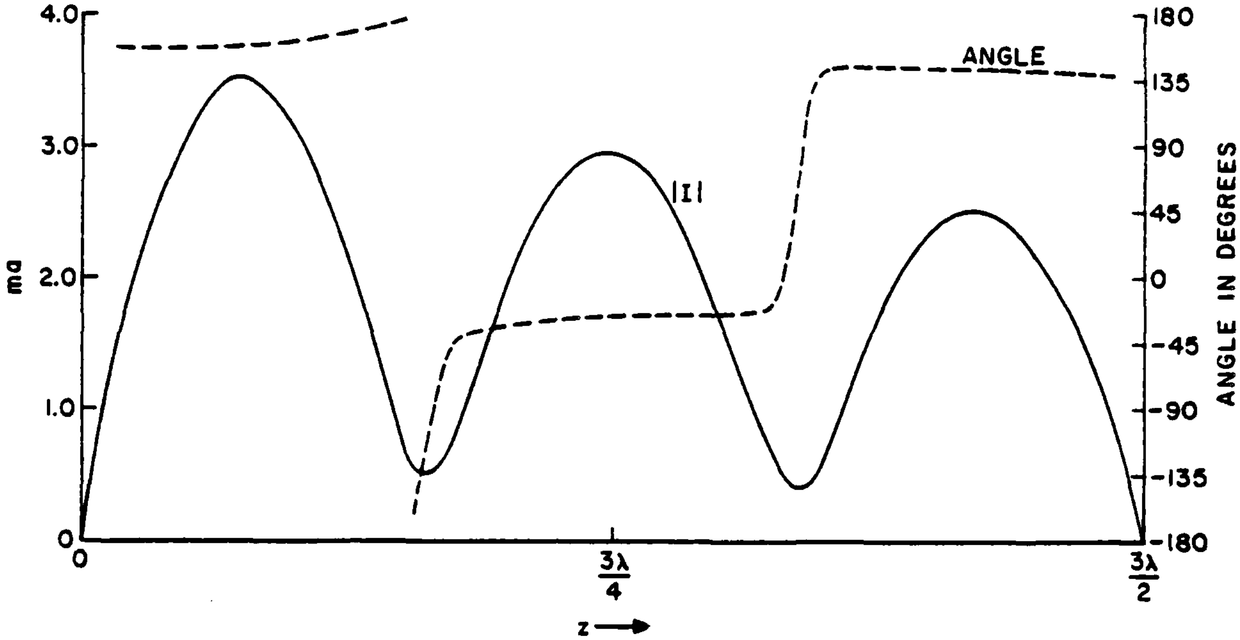


Fig. 17a - Current on a 1 1/2 wavelength unloaded linear scatterer. $\Theta_i = 30^\circ$. $|\vec{E}_i| = 1.0$. $2\pi a = 0.0635\lambda$. Pulse expansion functions [40] [57]. M = 31.

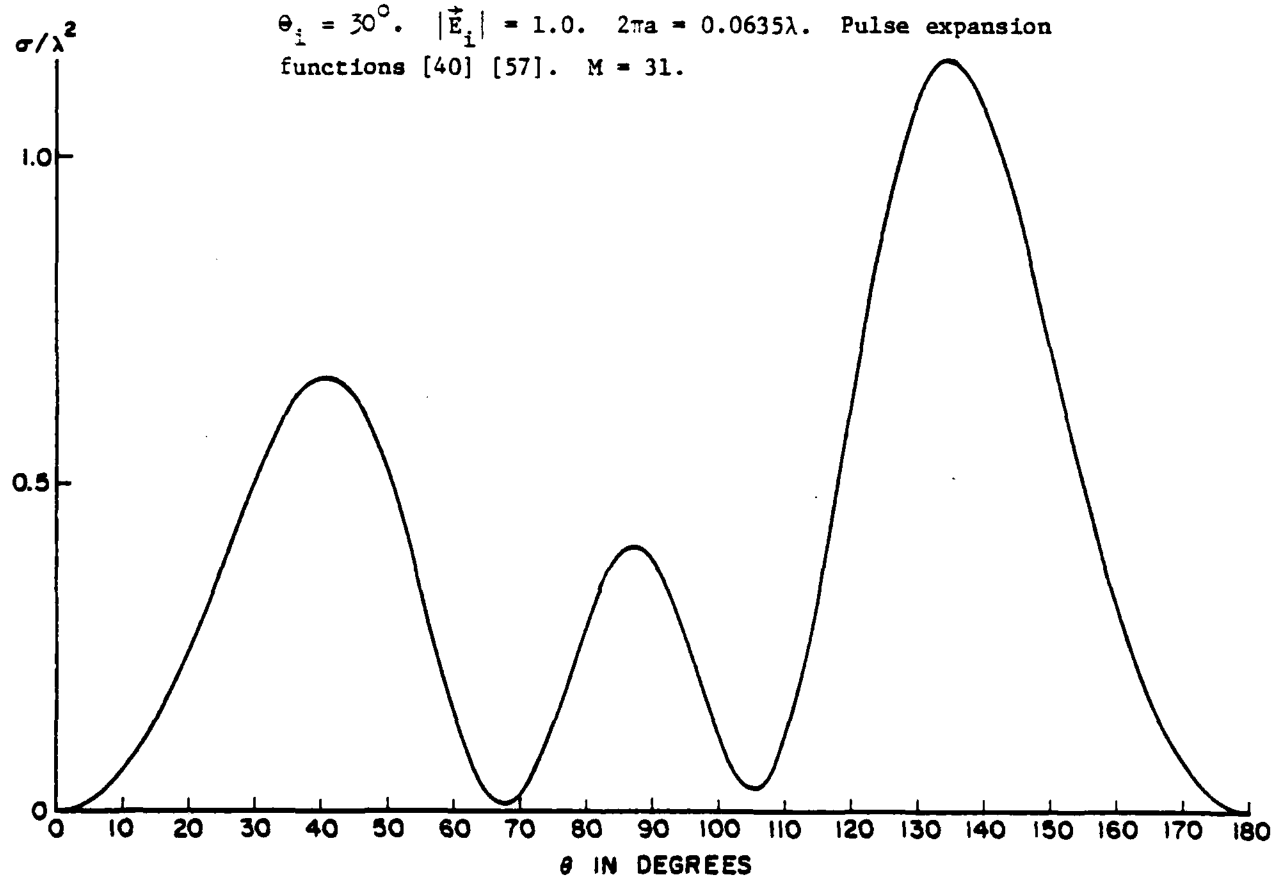


Fig. 17b - Bistatic radar cross-section pattern for a 1 1/2 wavelength unloaded linear scatterer. $\Theta_i = 30^\circ$. $|\vec{E}_i| = 1.0$.

2. Radiation or Scattering by a Single Thin Wire Acting in an Homogeneous Conducting Medium

Richmond's program (Table 4) can handle single-wire problems where the surrounding medium is homogeneous and other than free space. The wires can also be insulated. Examples involving use of this special capability are included in [49].

3. Radiation or Scattering by a Single Thin Wire Acting in the Presence of a Perfectly Conducting or Imperfectly Conducting Half-Space (ground).

The user-oriented codes ASAP (Table 5), WF-OSU/LLL2 [26], Richmond's modified program [28], WAMP (Table 6), and WF-LLL2A, WF-LLL2B are all suited for handling problems with wires acting over a perfectly conducting and/or imperfectly conducting half-space. Examples are included with the references given to those programs. Typical results can also be found in the technical reports and papers leading to these user-oriented codes [50] [51]. The program WIRES has been modified by Sarkar to handle the imperfect ground problem as well. He has presented a number of user-oriented codes for treating wire configurations including single-wire problems. One program, based on the method of reflection coefficients, is designed to handle arbitrary configurations of thin wires that are reasonably displaced from the plane surface of an imperfectly conducting half-space [52]. Three others have been written to treat problems where the wires involved are close to the surface of the ground [53] [54] [55]. Supplementary material on these FORTRAN codes can be obtained as described in the literature [50]-[55]. The latter three are based on the Sommerfeld formuation. Programming information is available in research reports [55] [56].

4. Design and Optimization for Single-Wire Problems

Programs have been developed using a code very similar to WRSMOM for treating design and optimization problems involving single wires [57]. For wires with multiple excitations the feed voltages can be determined to achieve some desired or specified pattern characteristics such as a given peak sidelobe level, nulls in certain directions, or optimum directivity. For wires that are loaded at various points along their lengths it is possible to calculate values for the load impedances that will result in given desirable or optimum performance characteristics as well. Procedures for accomplishing these objectives are available in the literature along with examples of their use [57].

5. Analysis, Design, and Optimization of Configurations of Several Wires With or Without Junctions Acting in Free Space

The program WRSMOM and other codes similar to WRSMOM have been used extensively for analysis, design, and optimization of one-, two-, and three-dimensional arrays of parallel wire antennas or scatterers acting in free space [59]-[64]. Configurations with given excitation and loading can be analyzed to determine current distributions, input impedances, radiation and scattering patterns, received power, etc. In design problems the excitations, loadings, interelement spacings, and even element lengths can be adjusted to achieve given desirable performance characteristics. A procedure has even been pointed out that combines the moment method with classical array design techniques enabling realization of patterns such as a Dolph-Chebyshev pattern (usually discussed in terms of point sources) with an array of parallel dipoles [65]. Optimization and constrained optimization procedures have been presented for determining excitations, spacings, or loading that will optimize some performance criterion such as gain, efficiency, or quality factor [43] [57] [64] [66]. This can be done even while maintaining pattern nulls in prescribed directions, or some specified maximum sidelobe level, or some other pattern or performance constraint.

WRSMOM and similar (pulses and point-matching) programs have also been used to calculate near-field distributions, interelement coupling between wires designed for operation at different frequencies and other parasitic effects, radiation hazards, and feed system requirements for configurations of straight parallel wires [44] [46] [61] [62] [67] [68].

A program similar to WIRES has been devised and is available for treating log-periodic dipole antennas and mutual coupling between elements in arrays of log-periodic dipole antennas [70] [71]. These antennas can be radiating either in free space or over a perfectly conducting ground plane.

The computer codes WF-SYR/LLL1 and WIRES described in Tables 2 and 3 respectively have been used extensively to analyze configurations of thin-wire antennas and scatterers that contain junctions [17] [19] [44] [69] [72]. Results have been presented for radiation and scattering by wires with sharp bends and also wire crosses. Some experimental results are also available for comparisons [73].

A program similar to wires has been written to treat analysis problems involving circular arrays of identical parallel thin-wire dipoles. Its main advantage is its relative computation efficiency resulting from careful use of array symmetries. The program is also useful for array synthesis to achieve a specified field pattern, and methods for designing required feed networks are provided [74] [75]. In this case many excellent analytical and experimental results are available for comparisons [76] [77].

Richmond's program and WAMP (Table 6) together with certain of their derivatives (Tables 5 and 7) have been used for treating a variety of complicated wire configurations. These include "stick" models and wire-grid models of aircraft, large low-frequency antennas with multiple junctions (ground effects are included in this case), multiturn loop antennas, thin-wire chaff for radar backscatter, and arrays of wire antennas [3] [43] [78]-[81].

6. Analysis, Design, and Optimization of Configurations of Several Wires With or Without Junctions Acting in the Presence of a Perfectly Conducting or Imperfectly Conducting Half-Space (Ground)

The user-oriented codes ASAP, WF-OSU/LLL2, Richmond's modified program [28], WAMP, WF-LLL2A and WF-LLL2B and Sarkar's modifications of WIRES [52]-[54] are all capable of treating complicated wire configurations including junctions acting in the presence of perfectly conducting or imperfectly conducting ground. Results for single-wire problems were referred to earlier. Results for more complicated configurations such as the large low-frequency antennas mentioned above have also been presented [80]. Other results can be found in reports containing specialized programs designed to handle arrays of either vertical or horizontal wires over ground [50] [51] [82]-[85]. Theoretical procedures have been suggested for design and optimization of arbitrary wire configurations for radiation or scattering in the presence of ground [86]. In theory all of the design, optimization, and constrained optimization techniques that are available for treating configurations in free space can be applied as well with the effects of ground included.

Special mention may be made at this point of a particular application of the WIRES program. WIRES has been used to predict bearing errors experienced by aircraft and caused by wire obstacles in the field of an airport VOR/DVOR station [87]. In this special application the ground is assumed to be perfectly conducting since the VOR is horizontally polarized and the incidence angles are normally small or shallow as measured from ground. A great deal of analytical work has been done on this problem since it was first treated by the method of moments [88]. However, the treatment of short wire obstacles by the WIRES program served to initiate the project and provide useful results for comparisons.

2.6 Programs for Time-Domain Treatment of the Electromagnetic Characteristics of Thin Wires and Rods

Although the vast majority of work done in the area of developing user-oriented computer programs for calculating the electromagnetic behavior of thin wires and rods has been done in the frequency domain, codes do exist for treating many thin-wire problems in the time domain. The transient behavior of a thin-wire structure subjected to a short pulse from a source such as radar or EMP can be determined via an inverse Fourier transform of frequency-domain data or by way of a direct time-domain solution. Miller and Landt have pointed out several advantages enjoyed by time-domain solutions over frequency-domain solutions for problems where transient effects are of interest [89]. Included among these are greater solution efficiency for many types of problems, the ability to handle nonlinearities, and the possibility of improved physical insight. EMC engineers are often interested in the electromagnetic characteristics of wire structures over a broad band of frequencies. The direct time-domain approach provides such information efficiently. Examples of wire structures that have been treated using a direct time-domain approach include straight wires, wire loops, "stick" models of aircraft, wire-grid models of aircraft, and wire-grid models of trucks [89]-[91]. These have involved both radiation and scattering problems and wires with both linear and nonlinear loading [92] [93].

One difficulty with the time-domain solution is that the resulting computer programs tend to be more extensive and complicated than their frequency domain counterparts and hence, somewhat less user-oriented. One code that has been used relatively frequently is denoted by TWTD (also called WT-MBA/LLL1A). This code was originated by Miller, Poggio, and Burke at MB Associates, San Ramon, California [94]. The code was adapted to its present form by Van Blaricum at the Lawrence Livermore Laboratory [95]. The program has been modified by Landt into a new form designated WT-MBA/LLL1B for treating more complicated structures. The latter will compute the induced time-varying currents on thin wire structures along with radiated or scattered fields. The method of subsections is used within the method of moments and the program user must specify the geometry of the structure and the time variation of the electric field applied at the center of each segment. If the structure is an antenna the applied field is specified (and is nonzero) only at excitation points. The induced current is first calculated and then used to compute the radiated or scattered fields (time-varying). All time-dependent quantities may be transformed to the frequency domain so that spectral characteristics can be studied. Antenna input impedance, gain, and radar cross-section can be calculated if desired. The wires can have resistive loading and the configuration may involve multiple wire junctions. A user manual for WT-MBA/LLL1A including program listing is available [95]. A manual for WT-MBA/LLL1B can be obtained [96] from the National Technical Information Service. A card deck can be supplied by the Electromagnetics and Systems Research Group at the Lawrence Livermore Laboratory, Livermore, California 94550. An abbreviated technical description is contained in [27].

Some of the earliest work on a direct time-domain solution for thin-wire antennas and scatterers using the method of moments was done by Sayre [90] [91]. Pulse functions were used in this case both to describe the current along the wire and also to describe the time dependence of the current. The program manual contains a program listing and illustrative computations for some canonical problems including a straight wire excited by a unit voltage step and for a straight-wire scatterer excited by a plane wave with unit step time dependence. Similar results are provided for a wire loop. Frequency domain information is again obtained via transform methods.

Both computer programs mentioned in this section are restricted to treatment of wire configurations in free space.

2.7 Conclusion

In this chapter several user-oriented computer programs were pointed out that are useful for frequency-domain or time-domain treatment of the electromagnetic characteristics of thin wires and rods. The list of programs suggested and references given is by no means exhaustive. The objective has been simply to mention, for each of the commonly used sets of current expansion functions, one or two computer codes that are both user-oriented and readily available for use by practicing engineers. In the next chapter attention is focused on available programs for frequency-domain treatment of two- and three-dimensional perfectly conducting or non-perfectly conducting (penetrable) bodies.

3. FREQUENCY-DOMAIN TREATMENT OF THE ELECTROMAGNETIC CHARACTERISTICS OF PERFECTLY CONDUCTING OR IMPERFECTLY CONDUCTING (PENETRABLE) BODIES

3.1 Introduction and Use of Wire-Grid Models

The use of wire-grid models of solid conducting bodies for analysis using a thin-wire computer code was suggested in the last chapter. This technique has yielded acceptable results for a variety of problems of practical interest especially where distant field distributions are of primary interest. Bodies that have been modeled in this manner vary all the way from simple rectangular conducting strips and plates to aircraft [3] [97] [98]. One obvious difficulty of a method-of-moments solution of this type is that the number of simultaneous linear equations to be solved increases dramatically with the electrical size and complexity of the body being treated. Although progress has been made towards development of techniques for handling larger and larger problems the essential difficulty remains [99]. In addition it has been pointed out that while this method is capable of providing reliable far-field results it cannot be depended upon for accurate indications of current distributions and near-field quantities [100]. Nonetheless, the wire-grid technique remains a useful analysis tool for some problems.

Other approaches to the treatment of solid bodies that are based on the method of moments include a treatment of bodies-of-revolution and techniques that involve use of two-dimensional segments or patches that are analogous to the subsections used for wires. The sections that follow in this chapter describe the user-oriented computer programs that are available for analysis of the electromagnetic characteristics of conducting and penetrable bodies using these approaches.

3.2 Bodies of Revolution

It is reasonable to assume that the method of moments has been applied most frequently in the general electromagnetics area to problems involving thin wires and rods. It is likely that electrically small conducting bodies of revolution stand next in line in this respect. One of the earliest applications of the method of moments as suggested by Harrington and his coworkers was treatment of electromagnetic radiation and scattering from perfectly conducting bodies of revolution of arbitrary shape [7]. Subsequent research led to development of a user-oriented computer code and supporting descriptive material that are readily available to practicing engineers [101]-[103]. The code is useful for treating radiation and scattering by conducting bodies that can be represented by closed surfaces or shells with maximum diameters of about two wavelengths. (Processing time becomes prohibitive for larger bodies.) Examples of such bodies include solid conductors such as spheres and closed cylinders, zero thickness conductors such as disks and open cylinders, bodies not intersecting a central axis such as washers and toroids, bodies with points such as cones and cone-spheres, bodies with edges such as disks and open cylinders, and certain bodies with corners. For a given problem the computer code is capable of calculating a) the generalized impedance matrix and its inverse;

b) the induced current distribution, scattered field, and bistatic radar cross-section pattern due to an axially incident plane wave; c) the current distribution, radiation field and power gain patterns of a body excited through one or more rotationally symmetric apertures; and d) the backscattered field and monostatic radar cross-section patterns from a body irradiated by an obliquely incident plane wave.

In each case the problem geometry is defined through a generating trace or curve that can be rotated about an axis to create the body of revolution. Bevenesee [16] has presented a useful independent analysis of the computer code and points out (among other things) that the solution convergence should be rapid if both the total length of the generating curve and the maximum circumference of the body are less than one wavelength in dimension. Accuracy of computation depends on the relative smoothness of the generating curve and on the type of excitation. Normally acceptable results can be obtained in reasonable time for scattering problems involving smooth bodies of up to two wavelengths in diameter.

The body-of-revolution codes are written in FORTRAN and the listings and descriptive material are available from a number of sources [101]-[103]. Card decks can be obtained by writing the program authors directly. The code has been applied by researchers to a variety of problems including calculation of induced current distributions and scattering patterns from missile-like bodies immersed in an incident field, low-frequency coupling through apertures in missile-like bodies, and calculation of navigational bearing errors caused by the presence of metallic bodies of revolution near VOR/DVOR airport stations [87].

The original body-of-revolution code is on deposit with the National Auxiliary Publications Service. Both microfiche and photocopies of the program listing and supplementary material can be obtained by ordering NAPS document 02307 from ASIS/NAPS, c/o Microfiche Publications, P. O. Box 3513, Grand Central Station, New York, New York 10017.

The original body-of-revolution program does not include a capability for calculating near-field distributions from the computed currents. This desirable capability has been provided through a modified version of the body-of-revolution code presented by Bevensee [104]. The new version called S3F-SYR/LLL1 is essentially identical to the original program in other respects. Both are limited to conducting bodies in free space only.

An abbreviated description of S3F-SYR/LLL1 is available [27]. The report [104] as well as source decks and listings are available from the Electromagnetics and Systems Research Group at the Lawrence Livermore Laboratory.

The original body-of-revolution code was devised over a decade ago. Since that time other codes have been presented that offer certain advantages. Bevensee's modified version is one example. One additional example should be mentioned. Wilton and Glisson [105] recently published an alternative program that appears somewhat better able to treat bodies involving edges and points such as disks and cones. The program has been applied extensively to the analysis of missiles with gaseous plumes. The code is also intended for treatment of closed dielectric bodies-of-revolution. Shortly after their original program was made available

Harrington and Mautz presented codes for treating the same kinds of problems as the original code only for loaded bodies of revolution [106] [107] and also for handling problems involving radiation by a current element radiating in the presence of a conducting body [108]. The reports referenced here contain program listings and results for certain examples. The latter program is valid for current elements both inside and outside of the closed body and hence is valid for both radiation problems and resonators. The program can be extended for treating more complicated antennas, such as wires or arrays of wires radiating in the presence of a body of revolution.

Harrington and Mautz have also pointed out that solutions obtained via the codes mentioned above degenerate near frequencies corresponding to interior resonances of the conducting surface treated. To remedy this they use a "combined-field" solution, first proposed by others [109], which exhibits no such adverse behavior [110]. The corresponding research reports contain listings of the revised FORTRAN codes together with sample applications of the method [111] [112]. A "combined source" solution has also been suggested as an additional remedy to enhance treatment of aperture radiation problems [113]-[115]. The latter will be discussed in the next chapter of this report.

The three body-of-revolution codes (Harrington-Mautz, Bevensee, Glisson-Wilton) are all reasonably user-oriented and available to practicing engineers. They have all been applied to a variety of very practical problems. Some of these will be mentioned briefly later in this report. As mentioned earlier these programs are restricted to analysis of bodies in free space. The first two are restricted to use with loaded or unloaded conducting bodies. The Glisson-Wilton program applies to conducting or closed dielectric bodies of revolution. That code is described and listed in [105].

3.3 Bodies of Arbitrary Shape

The method of moments has also been applied for treatment of radiation and scattering by bodies of arbitrary shape acting alone or in some cases in the presence of connected or unconnected wires. Generally speaking a surface-patch approach can be used in place of the wire-grid technique. Results indicate that quantities close to the body may be computed more accurately using this approach and fewer unknowns are required per unit surface area. The surface patch can be thought of as an extension to the segment or subsection described earlier for wires. Two perpendicular surface current components are required for each patch so that the number of unknowns and hence, linear equations to be solved, should be double the number of patches used. Two-dimensional or rectangular pulse current expansion functions were used by Knepp and Goldhirsh [116] in their early formulation for arbitrary bodies. Examples given included a radiating dipole above a conducting cylinder of finite length and a monopole mounted on the fuselage model of a helicopter. Pulse expansion functions were also used by Albertsen et al. [117] in their analysis of arbitrary bodies having one or more connecting wires. A computer program was prepared to compute radiation patterns of VHF monopole antennas mounted on cylindrical satellites. An option was included for attaching straight booms to which flat rectangular solar cell panels can be attached. Examples and program details are presented in [118]. An independent description and evaluation of their program (denoted by H3F-TUD1) has been prepared by individuals with the Electromagnetics and Systems Research Group at the Lawrence Livermore Laboratory from whom source decks, listings, and supplementary descriptive material can be obtained [14]. Wang et al. devised a surface patch approach using piecewise sinusoidal functions to describe the current in one direction and pulses in the other to treat conducting bodies of arbitrary shape [119]. Examples of their approach have been restricted primarily to surfaces consisting of connected rectangular plates. Newman and Pozar extended this work, modeling composite wire and surface geometries by using piecewise sinusoidal functions on the wires and also for both components of surface current on each patch. Several examples have been presented for wires connected to conducting surfaces in problems where input impedances are of interest [120]. Singh and Adams [172] used similar expansion functions to treat scattering problems. A promising method for treating scattering by arbitrarily-shaped objects in free space by using planar triangular surface patch models has been suggested by Wilton et al. [121]. This method is capable of handling either open or closed and arbitrarily-curved structures of finite extent and has been applied for treatment of scattering by a number of objects including a sphere.

Progress with computer code development for treating surfaces of arbitrary shape has not reached the state enjoyed by codes for wires and bodies-of-revolution, at least from the user's point of view. However, two key programs have reached user-oriented form. Burke and Poggio have combined a surface patch approach suitable for bodies of arbitrary shape similar to the one suggested by Albertsen et al. [117] with a wire code similar to WAMP (Table 6) to construct a general analysis program for analyzing the electromagnetic response of an arbitrary structure consisting of wires and surfaces in free space or over a ground plane. The program treats both radiation and scattering and computes current distributions, near-field distributions, and radiation patterns. This very general program, denoted by NEC (Numerical Electromagnetics Code) is described in detail in a three-part document consisting of a theoretical description, program description, and user's guide [122]. Because of the complexity of the problems involved in treating arbitrary structures the NEC and all other codes mentioned in this section are limited to structures that are electrically small (a few wavelengths in maximum dimension). Source decks and descriptive material for the NEC can be obtained from the Electromagnetics and Systems Research Group at the Lawrence Livermore Laboratory.

The second of the two user-oriented codes mentioned above for treating arbitrary surfaces is called GEMACS (General Electromagnetic Model for the Analysis of Complex Systems) [123]. This is a very large program with broad capabilities that include many of the features and inherent procedures contained in the NEC. GEMACS is a highly user-oriented general purpose code designed for gradual development and incorporation of a variety of techniques for electromagnetic analysis of complex systems including thin wires, surfaces, etc. The code which is constantly being augmented and updated was compiled by the BDM Corporation, Alburquerque, New Mexico. Information on possible applications and current capabilities of GEMACS can be obtained by contacting K. R. Siarkiewicz, Project Engineer, RADC/RBCT, Griffiss AFB, New York 13441.

3.4. Characteristic Modes

a. Conducting Bodies

In an effort to provide greater insight into the electromagnetic behavior of conducting bodies and to reduce in general the size of matrices needed for computations Harrington and Mautz presented a theory of characteristic modes for conducting bodies. Using the modes originally defined by Garbacz [124] they extended the concept and presented computer programs for calculating the characteristic modes of wire objects and bodies of revolution [125]-[129]. These modes are of theoretical value because they simultaneously diagonalize the generalized impedance matrix and the scattering matrix of the body, a useful property for problems of pattern synthesis and parameter optimization. The codes are available in the research reports and have been used in studies involving missile decoys and small antenna systems.

Methods have also been devised for controlling the characteristic modes of conducting bodies. Any real current can be made the dominant mode current of a conducting body. If no other current contributes significantly to scattering then the scattering pattern can be that of a synthesized characteristic mode. Harrington and Mautz have presented methods for finding the real current necessary for least squares pattern synthesis, with or without constraints and also for optimizing certain electromagnetic characteristics of the body. FORTRAN computer codes for these applications are available in the literature [130] [131].

Characteristic modes have also been defined for N-port scattering and antenna systems where N-port scatterers are those having N ports to which lumped impedance loads are connected. Again, computer codes have been presented for scattering and antenna pattern synthesis through judicious selection of reactive loading [132]-[136] and for more general impedance loading [137].

The synthesis and optimization procedures mentioned above depend on substantial excitation of the dominant mode current and, hence, are applied mainly at frequencies near the resonance region. Schuman [138] has specialized the method of characteristic modes to low-frequency applications with arbitrarily shaped conducting bodies. The report contains program listings and includes examples for systems of thin wires.

b. Penetrable Bodies

A procedure for applying the method of moments to problems involving scattering by material bodies using a volume formulation is discussed by Harrington [9]. A revised version based on use of equivalent surface currents was later specialized for homogeneous bodies of revolution by Mautz and Harrington [139] and for material cylinders (two-dimensional problems) by Chang and Harrington. The latter couples the general method with the theory of characteristic modes for material bodies [140] to create computer codes for calculating characteristic currents and scattering cross-section patterns of material cylinders. Code listings are included in the report [141]. The former has been used to devise codes for calculating equivalent surface currents and scattering patterns for dielectric bodies of revolution excited by an axially incident plane wave. Program descriptions and listings are included in the corresponding research report [142]. A theory of characteristic modes based on a volume current formulation rather than on equivalent surface currents was presented earlier [143]. An early treatment of material bodies using the equivalent surface current approach was performed by Harrington and his coworkers as one of the original tasks performed [107].

3.5 Two-Dimensional Problems

A treatment of two-dimensional scattering and radiation from a perfectly conducting cylinder of arbitrary shape was presented by Wallenberg [144]. His study was one of the first undertaken using the method of moments and the report points out many of the problems and concerns characterizing the research at that time. Wallenberg presents codes for calculating current distributions, radiation patterns due to aperture excitation, and scattering cross-section patterns [144] [145]. It was pointed out earlier that Chang and Harrington [140] [141] have dealt with scattering from two-dimensional material (penetrable) cylinders.

Two user-oriented computer programs designed for treating two-dimensional conducting cylinders have been deposited with ASIS/NAPS.

Both are written in FORTRAN as usual. The first, authored by Richmond [146], is intended for frequency-domain analysis of radiation and scattering by polygonal conducting cylinders in free space. Attention is restricted to the TE case (incident electric field perpendicular to the cylinder axis). The document number is NAPS-0226. The second program was written by Auckland and Harrington [147] to handle essentially the same problem with attention restricted instead to the TM case (incident magnetic field perpendicular to the cylinder axis). This document number is NAPS-02738. Supplementary material for both programs can be obtained from ASIS/NAPS, c/o Microfiche Publications, P. O. Box 3513, Grand Central Station, New York, New York 10017.

4. FREQUENCY-DOMAIN COUPLING OF ELECTROMAGNETIC WAVES THROUGH APERTURES IN CONDUCTING BODIES

4.1 Introduction

Problems associated with the coupling of electromagnetic energy through apertures have received considerable attention in recent years. These problems are particularly relevant to the EMC area because of related electromagnetic interference. Applications of the theory vary from a consideration of electromagnetic energy coupled into or out of aircraft and missiles to energy coupled into or out of computers.

Classical results in aperture coupling are limited to a few simple aperture shapes such as the long slot and the circular slot in a perfectly conducting plane screen. The classical literature on the subject is voluminous and is covered adequately elsewhere. A good review of research in this area can be found in [148].

4.2 Aperture in a Plane Conducting Screen

Harrington and Mautz have presented a general formulation based on the method of moments for treating aperture-coupling problems [149] [150]. It applies to any two regions that are isolated from each other except for coupling through an aperture or apertures that serve to join the regions together. The procedure has been applied to a rectangular aperture in a perfectly-conducting plane screen that is irradiated by a plane wave. The computer program written to deal with this problem (coupling by rectangular apertures in plane screens) is available [151]. A code is also available for treating rectangular apertures in rectangular waveguide [152]. That program, designed to calculate the admittance seen by the waveguide, the aperture fields, and desired radiation gain patterns, is on deposit with NAPS. Descriptive material can be obtained in the usual way [153]. The document number is ASIS/NAPS No. 03178.

The problem of electromagnetic coupling through a rectangular aperture in a plane screen has also been treated by Adams and Warren [154]. The basis for their work is Babinet's principle which relates the aperture-coupling problem to the problem of scattering by the complementary obstacle, which in this case consists of a perfectly conducting rectangular plate. A wire-grid model of the plate is analyzed using one of the aforementioned thin-wire codes to calculate the scattered fields which in turn can be used with Babinet's principle to find the fields coupled through the aperture in the original problem. The Adams-Warren program, denoted by WONDER, computes aperture fields, near- and far-fields beyond the aperture, and coupling to loaded wires beyond these apertures. The program is written in FORTRAN. The program description, listing, and illustrative examples are available in [154]. Additional information relating to the technique may be found in [155].

Graves et al. used Babinet's principle to calculate coupling through circular apertures in conducting screens [156]. Their approach is similar to the Adams-Warren technique except they treat the complementary obstacle (a disk in their case) directly as a body of revolution rather than employ a wire-grid model. They have presented comparisons for a number of interesting examples with results from special approximate techniques developed for applications at both high and low frequencies. An abbreviated description of their code is available in [157].

Butler and Umashankar have devised a formalism similar to the Harrington-Mautz procedure mentioned above for treating coupling through an aperture in a plane conducting screen [158] and also for coupling to a thin wire located behind an aperture in a plane screen [159]. Examples of the latter have included coupling to thin finite-length wires through thin slots (also of finite length) in the screen.

Coupling through long slots in infinite ground screens is treated in [160]-[165]. The program SDSLOT described in [160]-[162] treats an arbitrary plane wave incident upon a single long-slot aperture or two parallel-slot apertures in an infinite plane screen. The slots may be as wide as 10 wavelengths. A computer program listing and description is included in [162]. The computer program is on deposit with NAPS (ASIS-NAPS Document No. 02851) and can be obtained in the usual way [161]. The computer program described in [163] treats the long-slot problem with line source excitation by using the general formulation of Harrington and Mautz [149] [150]. Their theoretical approach has also led to analysis of coupling through a long, thick slot (i.e., a long slot in a thick ground plane) as treated in [164], [165]. A description and listing of the computer code for thick slots is included in [164]. The cross section of the slot may vary. Computations show that significant coupling may be obtained through narrow, thick slots via a resonance phenomenon [165] [167].

Coupling through an annular-slot aperture in an infinite plane screen is treated in a recent report [166]. The circular aperture is included as a special case. A listing of the code is presented in the report along with a description of the program.

4.3 Aperture in a Conducting Body of Revolution

A computer program has also been written for calculating fields coupled through apertures in conducting bodies of revolution [168] [169]. The procedure used in this case also follows from the Harrington-Mautz formulation mentioned earlier [150]. The program computes fields interior to a perfectly conducting empty cavity of revolution with a rotationally symmetric aperture that is irradiated by a plane electromagnetic wave. This FORTRAN code has been used in the treatment of a number of practical problems involving bodies such as aircraft fuselages and missiles that can be modeled at least in part by bodies of revolution. The code can be extended for use with apertures that are not rotationally symmetric [168]. The program is listed in [170] and theoretical details can be found in [171]. An abbreviated description of the code, denoted by BOR3, is also available [157].

5. APPLICATION TO SYSTEMS PROBLEMS AND CONCLUSION

The purpose of this report has been to describe the method of moments briefly and to point out certain general-purpose, user-oriented computer programs based on the method that are readily available for use by engineers working in the areas of electromagnetics and electromagnetic compatibility. The method was described without detail and only in terms of its application to thin-wire problems. Useful computer codes were pointed out and described for handling various canonical problems involving the electromagnetic characteristics of thin wires, conducting bodies, penetrable bodies, and aperture coupling. It was suggested that while most physical systems are far too complicated for detailed analysis there often exists a closely related canonical problem that can be treated successfully by existing techniques and/or computer codes. Results obtained for such problems may serve to bound those of the related system problem and provide valuable physical insight.

For the most part each of the computer programs mentioned here is designed to treat a certain class of problems. Those described in Chapter 2 are intended for problems of radiation and scattering by configurations of thin wires. The codes of Chapter 3 are designed to handle radiation and/or scattering by two- and three-dimensional conducting or penetrable bodies. The programs mentioned in Chapter 4 are intended for particular aperture coupling problems such as a rectangular aperture in a plane screen, a rotationally symmetric aperture in a body of revolution, etc. The two general computer codes NEC and GEMACS mentioned earlier are notable exceptions (see Chapter 3). These are intended for analysis of more complex systems and are in a continuing state of development. They consist of combinations of existing basic programs and are intended to include additional codes that may be devised in the future.

Examples exist where combinations of the codes described in this report have been used to analyze certain compatibility problems and characteristics of large complex systems. For example, the Harrington-Mautz body-of-revolution code, the WIRES program, and the BOR3 aperture-coupling code were combined with a particular circuit-analysis program in an attempt to analyze a susceptibility problem of a certain airborne missile. As another example the Wilton-Glisson body-of-revolution program has been used with a code which calculates the parameters of gaseous plumes in an elaborate analysis of the effects of a plume on the electromagnetic characteristics of missiles in flight [173]. It is anticipated that attempts to apply combinations of programs to complex systems will occur more and more frequently in the future.

The method of moments is useful primarily for treating problems where the maximum dimension of a problem geometry measures a small number of wavelengths. For higher frequencies other analysis techniques such as GTD and STD are useful [174]. These were not discussed in this report although they too have led to development of computer codes for system analysis. Hybrid techniques have also been presented which combine these with the method of moments for various applications [175] [176].

The references listed in this report are only typical of work with the method of moments that has taken place over the past ten to fifteen years. Many worthy accomplishments are not listed. A complete list is simply beyond the scope of this document. Additional information on available computer programs and techniques based on the method of moments can be found in [177].

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COMPUTER PROGRAMS FOR EMC BASED ON THE METHODS OF MOMENTS.(U)

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